AN EXPERIMENTAL INVESTIGATION INTO LOW TEMPERATURE MACHINING OF SOME ENGINEERING MATERIALS

by

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CERTIFICATE

This is to certify that the present work entitled, "AN EXPERIMENTAL INVESTIGATION INTO LOW TEMPERATURE MACHINING OF SOME ENGINEERING MATERIALS", has been carried out under my supervision and has not been submitted elsewhere for the award of a degree.

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Ajai Kr Pathak

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ABSTRACT

Materials having high strength and low thermal conductivity are being used increasingly. Despite advances in cutting tool materials, considerable difficulties are experienced while machining materials with low thermal conductivity. Due to enormous temperature rise tool wear becomes main problem. In many cases conventional cutting fluids become ineffective. In first part of the present work machining of mild steel at low temperature has been investigated. Liquid nitrogen has been used as a cooling agent. A study has been made about the effect of low temperature on cutting forces, temperature rise and growth in tool wear while cutting with high speed steel tools. It has been established that tool life increases remarkably at low temperature. Cutting force also decreases at low temperature.

In second part of the work effect of low temperature on Abrasive Jet Machining of glass has been investigated. Increment in material removal rate at low temperature has been reported.

CONTENTS

CHAPTER I

INTRODUCTION

1.1 INTRODUCTION:

Machining under room temperature conditions is the most convenient and still most common process of producing components. Lot of theoretical and experimental results are available on machining at room temperature. Several researchers have also attempted hot machining process [1,2]. Hot machining is done to get some extra advantages which are not obtained at room temperature. In hot machining, heat is applied to the work piece material to reduce shear-strength in the vicinity of shear-zone. Machining of high strength heat resistant metals and alloys becomes easy due to considerable reduction in cutting forces.

Temperature rise during the cutting operation is the main cause of tool wear. At higher speed tool wear becomes very significant and adversely affects the production output. Alloy with low thermal conductivity put-up stiff challenge before a production engineer. Despite the use of cutting fluid, premature failure of cutting tool occurs. If such type of materials will be machined at low temperature, tool life is likely to increase.

At high temperature metals become more ductile hence built-up edge is formed. Due to formation of built-up edge cutting forces increase and surface roughness also increases. At low temperature metals become harder and shear angle will increase as expected. Due to the above reasons the cutting forces and the surface roughness can decrease.

As from the study of properties of materials, at low temperatures bcc and hcp metals become brittle and fracture toughness of metals reduce. It means brittle failure of metal can be obtained at lower stress and strain value.

Abrasive jet machining (AJM) and Ultrasonic machining (USM) processes are more suited for brittle materials. Hence these processes of machining are expected to become more efficient at low temperature condition.

1.2 LITERATURE SURVEY:

Very limited researchers have attempted to improve the cooling capacity of air by refrigerating it [3]. Olson (1948) using cooled air in a milling operation, reported 400 percent increase in tool life over air at room temperature. Pahlitzsch has presented test results using carbon dioxide gas and nitrogen gas as cutting fluids. He found an improvement in total life over air by 150% using CO_2 and 240% using N_2. Freon-12 was sprayed into the clearance space between the work and tool. Dramatically increment in tool life and reduction in cutting time was

reported [4*, 5]. Metal or alloy machined with greater ease, while using sub-zero coolant [6*]. A study was made on surface finish and hardening of work pieces made of stainless steel and titanium alloy while cutting with cemented carbide tools. It was established that surface finish improves as the temperature decreases [7]*. Pentland and Ektermanis [8] have suggested among the other things, the use of refrigerated abrasive slurry in ultrasonic machining for enhancing material removal rate. On the basis of mathematical model Dharmadhikari and Sharma [9] have tried to show the economical feasibility of using refrigerated abrasive slurry, in ultrasonic machining.

The literature survey reveals that very little is known about low temperature machining. It can be regarded as a new field of machining and can open new scope of research.

1.3 OBJECTIVE AND SCOPE OF THE PRESENT WORK:

The discussion presented in the preceeding section clearly reveals that the machinability of various metals, alloys and non metals can be increased at low temperatures. The basic objective of the present work was to see what would be the affect of low temperature in the deformation zone in a machining process. Fracture toughness of bcc and hcp metals and alloys decreases due to ductile to brittle transition. Discontinuous chips and low cutting forces were expected. Titanium and its

* Author could not find these references. However some information has been taken from the abstracts of these papers published in various Engineering Index.

alloys posseslow thermal conductivity and high strength. Machining of titanium under normal conditions poses enormous problem. Tool wear is extremely high and the usual cutting fluids are not efficient. The original plan of the present work was therefore to investigate the machining of titanium at low temperatures at length. However, due to considerable difficulties in its procurement the first part of the work was confined to machining of mild steel. In machining of mild steel liquid nitrogen has been used to create low temperature in cutting zone. The cutting forces, tool life and tool chip interface temperature have been investigated.

In the second phase of the work the Abrasive Jet Machining (AJM) of glass under low temperature condition has been investigated. One pilot experiment on low temperature machining of rubber have also been conducted.

CHAPTER II

PROPERTIES OF MATERIALS AT LOW TEMPERATURES

2.1 INTRODUCTION:

Research in cryogenic engineering during the late 1800s led to the liquefaction of oxygen (1877), following by nitrogen (1883), hydrogen (1891), and, finally, helium (1908). These fluids provided scientists the opportunity to conduct research at low temperatures. Various new properties of materials have been discovered, which are very useful from the engineering point of view. In the following pages some of the properties of materials, have been discussed, which are important from the mechanical engineering point of view.

2.2 ELASTIC PROPERTIES:

Elasticity means the atoms can move about their equilibrium position periodically changing inter-atomic distance [10]. At high temperature movement of atom about their equilibrium position increases, volume of the material increases. Due to increment in inter atomic gap intrinsic inter atomic force decreases. At low temperature this vibration of atom decreases hence intrinsic inter atomic force increases.

Elastic properties of a crystal is affected by lattice vibration. Elastic properties of crystal are determined primarily by strain dependence of harmonic frequency distribution $G(\omega)$ of the cristal lattice [11]. Frequency of vibration of crystalline prism can be determined with the help of elastic constant [12].

Elastic constants are the physical properties, relate stress to strain, or force perunit area to relative length change. Various experimental results are available which deals with the change of elastic properties at low temperatures. Fig. 2.1 show how various elastic constants vary with temperature between 0 and 300°K. Elastic stiffness of material increases by 5 to 15% during cooling. Theoretical explanation of elastic behaviours at low temperature is very complicated [10]. Although many scientist have tried but not a complete satisfactory theory has been developed.

2.3 SPECIFIC HEAT:

Heat capacity, C, is defined as the amount of heat required to raise the temperature of a system by a unit of temperature.

$$C = \frac{dQ}{dT}$$

The heat capacity per unit mass is called the specific heat or, sometimes, the specific heat capacity.

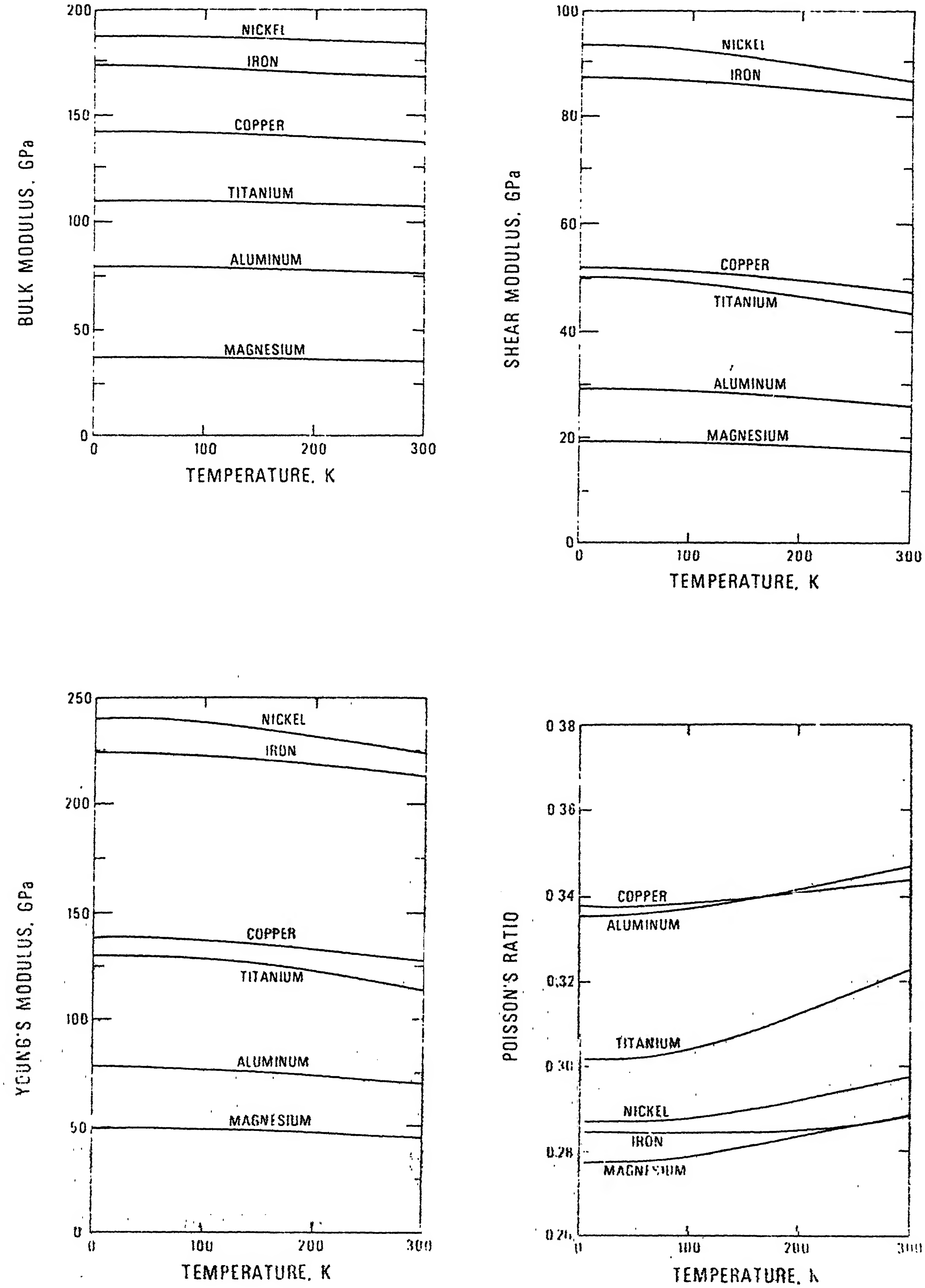


Fig. 2.1: TEMPERATURE VARIATION OF ELASTIC CONSTANTS FOR SIX METALS[10].

Before the advent of the quantum theory the values of the specific heats of solid were calculated using the classical theorem of the equi-partition energy. It was assumed that each atom or molecule in a solid was able to vibrate about a fixed point. This vibration can extened in three dimensions. Equi-partition of energy theorem ascribes an energy of 3 KT to each atom or molecule. From this assumption molar specific heat has the constant value $3R = 24.94\ J\ mol^{-1}\ deg.^{-1}$ This relation is very successful both at and above room temperatures. This relation fails to determine the specific heat at low temperatures.

Einstein (1907) tried to explain the decrease in specific heat at low temperatures on quantum theory.

Quantization of Lattice Vibration:

The energy of lattice vibration is quantized. The quantum of energy is called phonon in analogy with the photon of the electro-magnetic wave [13]. Elastic waves in crystal are made up of phonons. Thermal vibration in crystal are thermally excited phonons.

On the basis of quantum theory, Einstein suggested that the atoms oscillating at a frequency ν could not vibrate with any arbitrary amplitude but they could only have discrete value of energy separated from one another by a quantity h, where h is plank's constant [14]. Whilst Einstein theory showed why

the specific heat decreased at lower temperature, it was not entirely satisfactory. Einstein assumed that all the atoms vibrate with the same frequency and that they were independent of one another. This is obviously only a very rough approximation.

The Debey Theory:

In this system the atomic system is assumed to be an elastic continuum in which only certain frequency can be excited and maintained. These will be those which are able to set-up standing waves in the medium, any others will die out rapidly [14]. Debey assumed lattice vibrate with a upper limit to the vibrational frequencies. He developed a formula which correlate the specific heat with T^3 at low temperatures.

$$C_v \simeq 1944\ r\ \left(\frac{T}{\theta_D}\right)^3\ J\ mol^{-1}\ K^{-1}$$

$$= \beta T^3$$

where,

C_v = specific heat

θ_D = $h\nu/KT$

r = number of atom per molecule.

At high temperatures Debey specific heat yields the Dulong and Petit value. Success of Debey theory is very remarkable. It is based on simple model. Experimental value of specific heat closely agreed with the theoretical value.

Recent researches show that Debey theory is also not accurate in extrict sense. Over an appreciable temperature range, it is not accurate and does not agree with the experimental results [14].

From the above discussion, it is clear that specific heat is the strong function of temperature, particularly for $T \leq 200^{o}K$ [10]. Fig. 2.2 shows specific heat as a function of temperature for several types of material .

2.4 THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY:

Thermal conductivity correlates the two parameters heat flow and temperature gradient. For steady state unidirectional heat flow through an isotropic medium, this relationship is given by the equation,

$$\frac{\dot{Q}}{A} = - K \frac{dT}{dx}$$

where,

$\dot{Q}$ = Rate of heat flow

A = Area through which heat is passing

K = Constant of proportionality known as thermal conductivity.

The minus sign indicates the direction of heat flow is opposite to the gradient.

Thermal diffusivity, α, can be expressed in term of K, and C as,

$$\alpha = \frac{K}{\rho C}$$

ρ = density of material

C = specific heat of the material

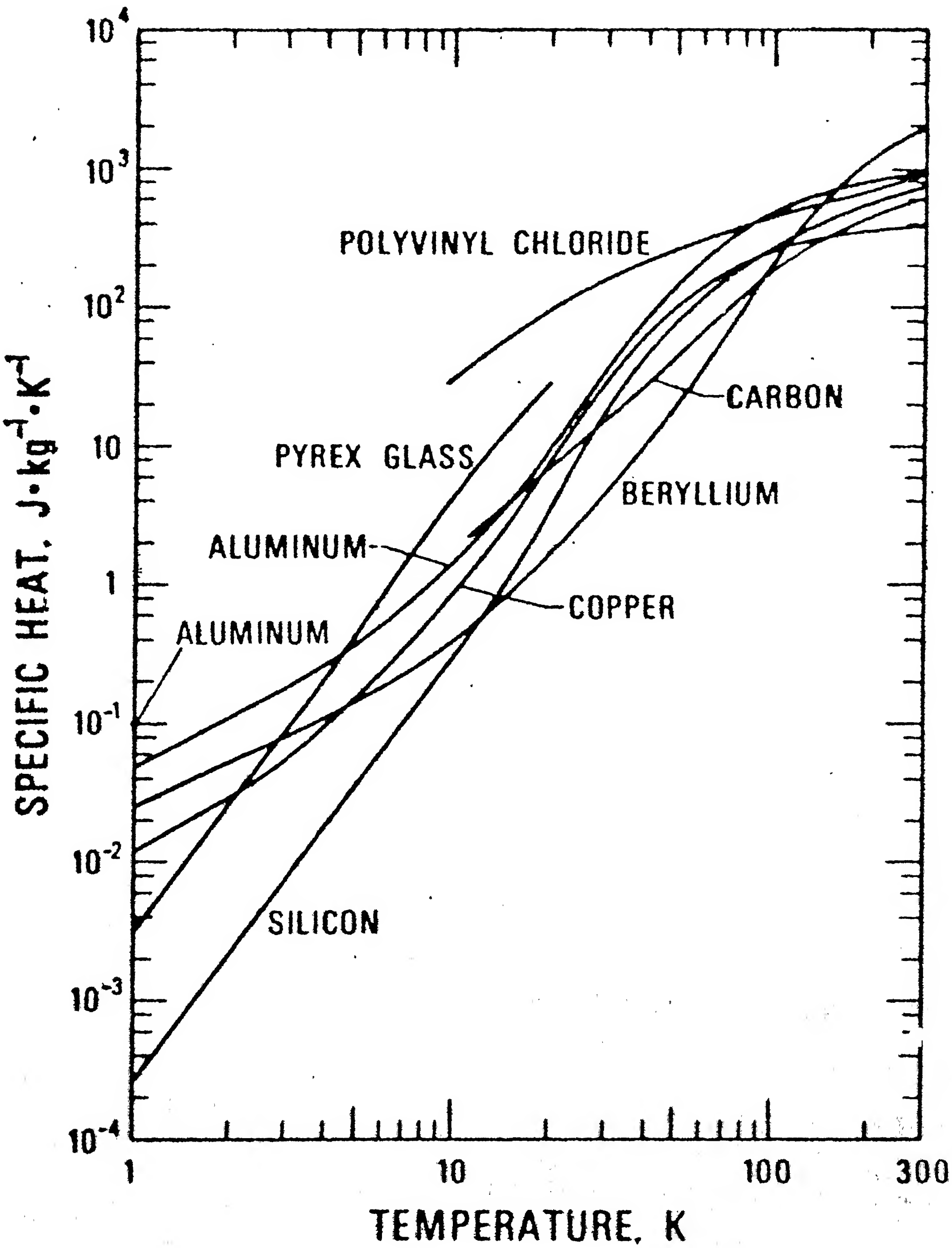


FIG. 2.2: SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE[10].

Mode of Heat Conduction:

Different type of material has different type of mode of conduction. In pure metal and dilute alloys the principal conduction mechanism is electronic, i.e. free electrons are almost solely responsible for the conduction of heat [15]. In case of highly alloyed metal the heat conducted by quantized lattice vibration (phonons) becomes more dominant. In non metal and structural material the heat conducted by free electrons completely seized. All the heat is conducted by phonons. In semi conductor material electron holes pairs conduction is present. Fig. 2.3 shows the heat conduction mechanism.

Thermal conductivity of metal is generally electronic type of conduction. Movement of free electrons is generally restricted by phonons, lattice imperfection, other electrons and magnetic fields. Lattice vibration and lattice imperfection play most significant role in restricting the motion of electrons. Electrons are scattered due to above reasons. Material imperfections becomes most important at low temperatures irrespective to physical and chemical imperfections[14]. Due to different typesof crystal imperfections,single value of conductivity can not be obtained at low temperatures.

In case of highly alloyed materials and non-metals the higher defect concentrations and lattice disorder increase the resistance to electronic and phonon heat flow. Resistance to

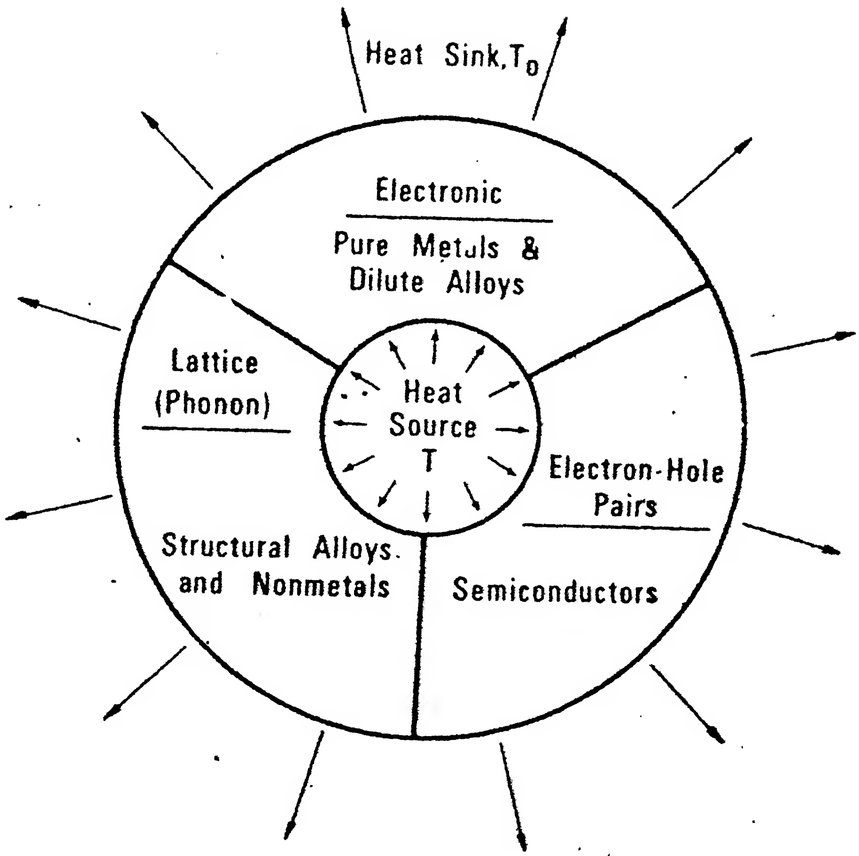


FIG. 2.3: HEAT TRANSPORT MECHANISM[10].

electronic flow is increases more significantly than the phonon heat flow [14]. Heat conduction by phonons become more dominant, consequently conductivity of alloy and non metal decreases.

Figs. 2.4 and 2.5 give an idea about the variation of thermal conductivity and diffusivity with change in temperature. It should be kept in mind here is a single curve for one particular material. But practically it is not true because materials are used in various alloy and mixture form. As the temperature decreased, the alloy thermal conductivity decreases approximately linearly. The temperature dependence of purer elements is complex [16]. The thermal conductivity initially increases reaches maximum, then rapidly decreases as the temperature approaches absolute zero.

2.5 MECHANICAL PROPERTIES:

Mechanical properties of materials are the most important properties for a mechanical engineer. Mechanical properties deals with the stresses applied on the materials and corresponding deformation. Yield strength, ultimate strength, elongation to fracture and reduction of area are the main points of concentration. Use of materials at low temperatures increasing day by day. Before using any material at low temperature, knowledge of the behaviour of the material at low temperature is essential. Mechanical properties of materials

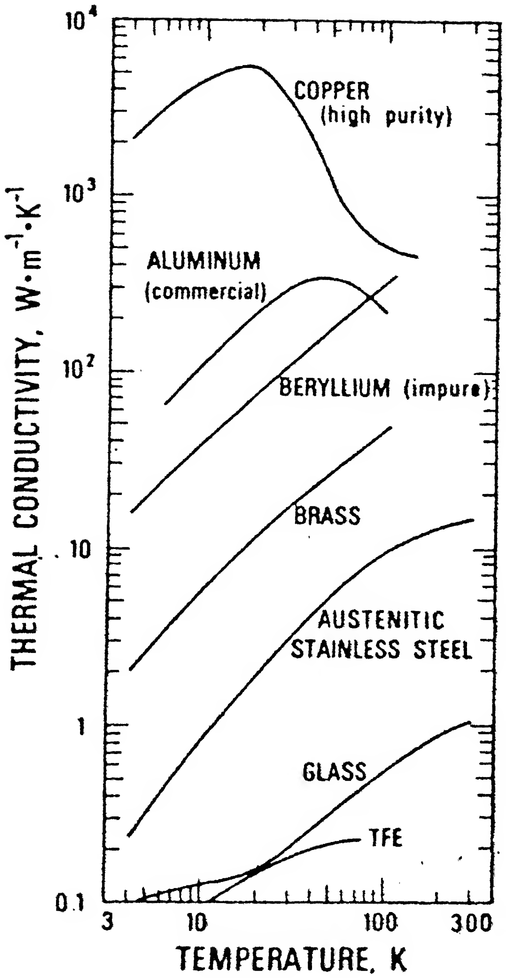


FIG. 2.4

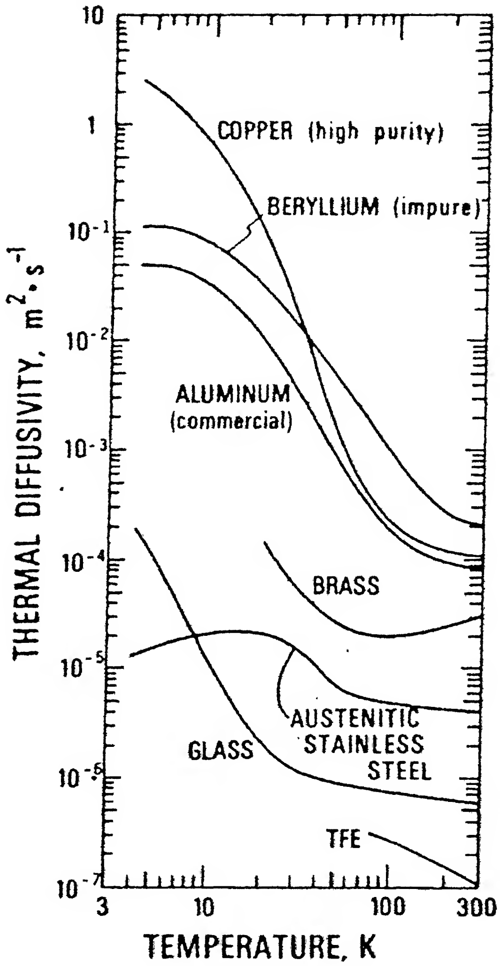


FIG. 2.5

THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY AS A FUNCTION OF TEMPERATURE[10].

change at low temperatures but change in the properties is not similar for all materials. It depends upon the crystal structure, composition and type of material.

2.5.1 Tensile Properties:

High temperature means higher order of thermal vibration of atoms and diffusion rates. Low temperature means lower order of thermal vibration of atomsand diffusion. Deformation in solid is only due to step-wise movement of dislocation through a lattice. There always exist a stress barrier surrounding the dislocations which restrict the motion of involved atoms [17]. Thermal agitation always helps the motion of dislocation. The deformation properties at low temperature are changed because there is less thermal activation available to assist the dislocations to overcome the obstacles. In absence of thermal activation more force is required to overcome the force barriers. This force barrier has controlling influence on the mechanical properties of the materials. As a result at low temperature yield and tensile strength of materials usually increase. Generally higher stresses are required to develop equivalent amount of strains.

This dislocation theory is verified by different behavior of yield strength of fcc and bcc lattices. Yield strength of fcc material increases by 20 to 50% while yield strength of the bcc materials increases by 100% [18]. In this

this way, it is clear that behavior of bcc material is more temperature dependent. fcc materials retain their ductility at low temperature, but bcc materials become brittle [19]. These are characterized by a ductile - brittle transition region which occurs over a narrow range. Below transition temperature the metal breaks in a brittle fashion with little or no plastic deformation. At low temperature thermal activation will not be so effective in helping the dislocations to pull away from their impurity atmospheres and the yield stress increases [14]. The reason why this effect is not observed in fcc metal is that in the fcc structure an impurity atoms produces a spherically symmetrical distortion of the lattice and it is only attracted to the edge dislocation. The screw dislocation are left free of impurity and can thus move under a much lower stress. In bcc lattice the impurity atoms cause a non-spherical distortion of the lattice and some of this strain can be relieved by the screw dislocations as well. Thus all the dislocations can be anchored by the impurity atoms [14, 20].

Various explanations are available for the different behaviour of material at low temperature. One of the more popular explanation is that the distorted area around dislocation in the bcc lattice can be assumed as 'hair like' in nature. Hair like means few atomsin diameter. Distorted area

around dislocation in the fcc lattice is assumed ribbon like (i.e. a few atoms in thickness by higher order of magnitude in width). That is why thermal fluctuation can easily aid the movement of dislocation and makes the yield strength of bcc lattice more temperature dependent [18]. In case of fcc, distorted area around dislocation is ribbon like, hence thermal agitation cannot easily help the dislocation to move. This is the reason that properties of fcc material is not very much temperature dependent. Characteristics of hcp alloy falls between the fcc and bcc alloys. In many cases it behaves more like the bcc alloy [18].

From the above discussion, it is clear that except in broad quantitative terms no theories which have yet been put forward have received complete acceptance [14, 21]. The reasons for this are mainly that the dislocations even in an annealed crystal usually occur in a very complicated network. State of knowledge in this area lacks a unifying theory based on atomic model of plastic flow and fracture. In absence of any theoretical explanation various emperical concepts have been developed.

Emperical approach can be classified into two groups, either transition temperature approach or fracture concept [18]. The transition temperature concept uses the emperical observation that properties of bcc materials undergo a drastic change at some temperature, called transition temperature. The

impact strength decreases drastically. It means the ductile to brittle transition of material take place at transition temperature. It must be known that under-lying causesfor ductile to brittle transition are still unknown. The other approach to brittle failure is based on fracture concept. It can predict the load at which fracture will occur or maximum defect size beyond which fracture will occur under given load conditions. This concept is not based on the fundamental atomic theory. Fracture concept is based on the macroscopic analysis of stress and strain.

2.5.2 Properties of Engineering Alloys:

Mechanical properties such as tensile strength, weld strength and toughness are very important for engineering alloys. Toughness evaluation is necessary because it reduces drastically for bcc structure. It is important to remember that effect of cryogenic temperatures on materials is primarily dependent upon crystalline structure. Therefore, summarised review of typical effects for bcc, fcc and hcp materials are given in Table 2.1. Temperatures generally incountered in cryogenic testing are the boiling points of liquified gases: e.g., $4^{o}K$ (helium), $20^{o}K$ (hydrogen), $77^{o}K$ (nitrogen) and $90^{o}K$ (oxygen).

(a) Iron Base Alloys:

Iron is the most widely used metallic element in structural metal and alloys. At room and cryogenic temperatures,

Table 2.1: Typical effects of cryogenic temperature on materials having fcc, bcc and hcp crystalline structures. Effect of decrease in temperatures (from 298° to 20°K) on alloy having .[18]:

Property	FCC Structure	BCC Structure	HCP Structure
Tensile strength	Increases 100 %	Increases 80-100 %	Increases 100 %
0.2% Yield strength	Increases 20-50 %	Increases 100 %	Increases 100 %
Elastic Modulus	Increases 20 %	Increases 20 %	Increases 20 %
Proportional limit	Increases 20-50 %	Increases 100 %	Increases 100 %
Elongation	Little or no effect	Large decrease (to nill ductility) at transition temperature	May have little or no effect (e.g. titanium) or a large decrease at transition temperature (e.g. Zinc and magnesium)
Toughness (as determined by notched tensile, impact, crack propogation, bend, fracture appearance etc.)	Generally little or no effect	Loss of toughness at ductile to brittle transitions temperatures.	May behave like fcc with little or no effect, or may become brittle (like bcc) at a transition temperatures.

the iron base alloys have either bcc or a metastable fcc crystalline structure. The bcc iron base alloys undergo a ductile to brittle transition. Transition temperatures range from above room temperature to as low as 100 - 200°K. It greatly depends upon composition and micro structure of the material [22 Highly pure iron possesses low tensile and yield strength but high ductility at room temperature. Reduction in temperature cause large increase in yield and tensile strength. At low temperature ultimate strength approaches the yield strength. Ductility and toughness are not severely affected until transition temperature (100 - 150°K) is reached [18]. After transition temperature, metal becomes brittle and show nil ductility. Ingot and wrought iron have greater strength and lower ductility at room temperature, but behave quite similarly. Generally transition temperature is much higher and may even be room temperature depending upon impurity and microstructure.

Eigi Fukashima [23] has tried to show that fracture of these alloys is not to be regarded as brittle fracture in the strict sense though it occurs abruptly. He observed a little plasticity for bcc alloys at cryogenic temperatures.

Low, medium and high carbon steel and cast iron possess a bcc structure and behave similarly as stated above. These types of metals undergo ductile to brittle transition. Due to various factor transition temperature may vary over wide range from above room temperature to 150 - 200°K.

The high alloy ferritic and martensite steel are affected much in the same fashion as the carbon and low alloy steels. There is also a temperature range in which these steels undergo a ductile to brittle transition (150 - 300^{o}K).

Austenitic stainless steels are alloys of iron with cromium and enough nickel or manganise. Many of these steels retain fcc structure from 298 to 4^{o}K. Due to different type of crystal structure it behaves quite differently at cryogenic temperatures than do the bcc iron alloy. At cryogenic temperatures large increase (100 %) in tensile strength, smaller increase (20 - 50%) in yield strength and little or no effect on ductility have been found [18]. However, several of these steels have total or partial transformation from austenite to bcc martensite. The properties of these type of materials are the combination of fcc and bcc materials.

Fig. 2.6 summarize the effect of cryogenic temperatures on the properties of iron base alloys.

(b) Nickel and Cobalt Base Alloys:

The crystalline structure of nickel and cobalt are fcc and hcp respectively. However, nickel-cobalt alloy in which nickel is about 10% possess fcc structure at room and cryogenic temperatures. Nickel-cobalt alloys are called super alloys and known for their superior elevated temperature (1000 - 1500^{o}K) properties. Very high strength may be achieved

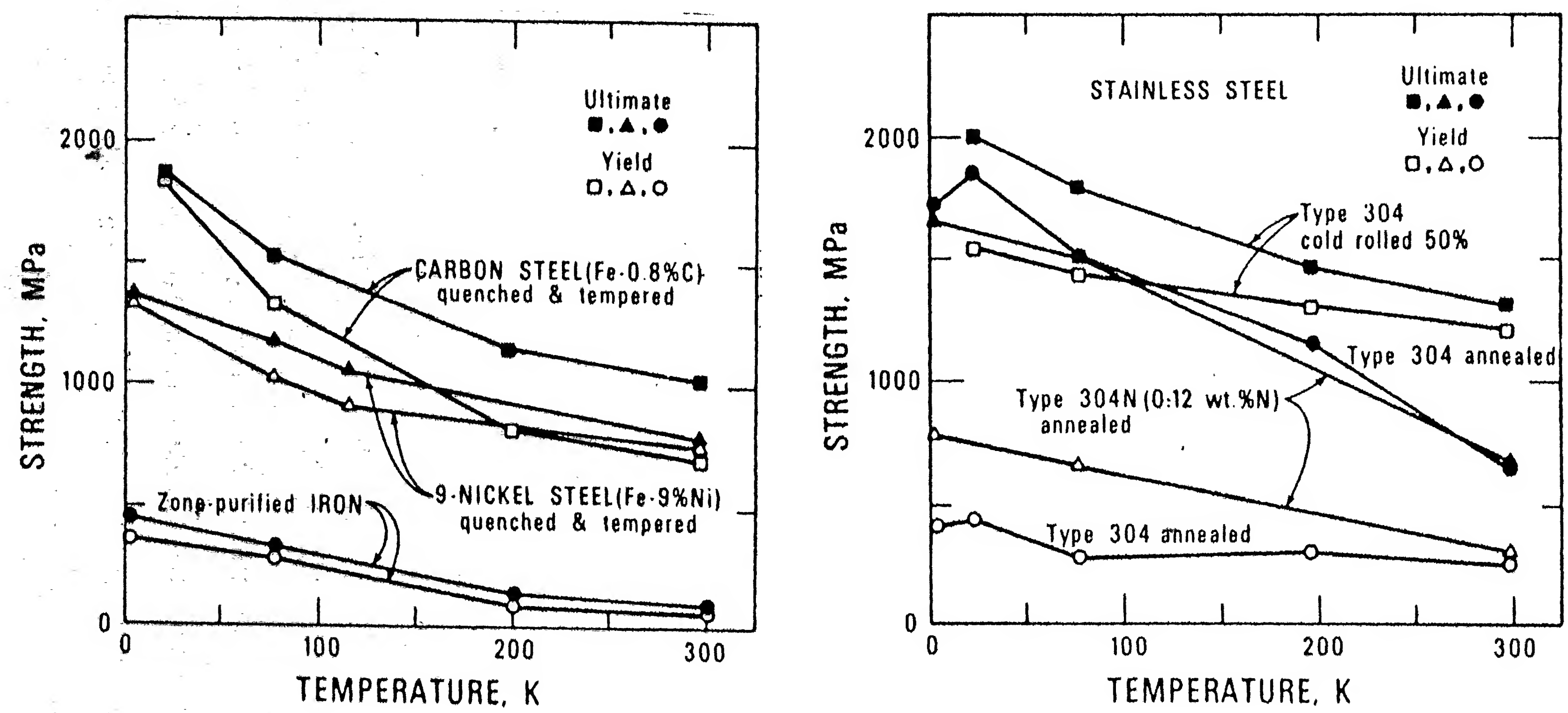


FIG. 2.6: YIELD AND ULTIMATE STRENGTHS AS A FUNCTION OF TEMPERATURE FOR IRON BASE ALLOYS[10].

in some super alloys by combinations of cold rolling and aging treatments. Annealed nickel and cobalt alloys show increase in tensile strength by 100 % ,yield strength of about 40 - 60% [18]. Low temperature has no effect on its ductility and toughness. Aged and cold rolled materials have increases of about 50 % for both yield and tensile strength. Fig. 2.7 illustrates the various properties of different nickel and cobalt base alloys.

(c) Aluminium Base Alloys:

Pure aluminium is soft, light and can strengthened considerably by alloying. It is nearly an isotropic metal. Aluminium and aluminium base alloys possess fcc crystalline structure. Similar to general fcc materials its tensile and yield strength increases. It retains it ductility and toughness at cryogenic temperatures. However, some Al -alloys lose their toughness at very low temperatures. Fig. 2.8 summarizes the effect of cryogenic temperatureson mechanical properties of typical aluminium alloys.

(d) Titanium and Titanium Alloys:

Titanium alloys, used in aerospace applications because of their low density and high strength at high temperatures and also useful at low temperatures. Titanium possess excellent corrosion resistance and good fabrication characteristics. Crystalline structure of titanium is bcc at higher temperatures (about 885°C) and hcp at lower temperatures. Addition of alloying elements changes the transformation temperature and also results

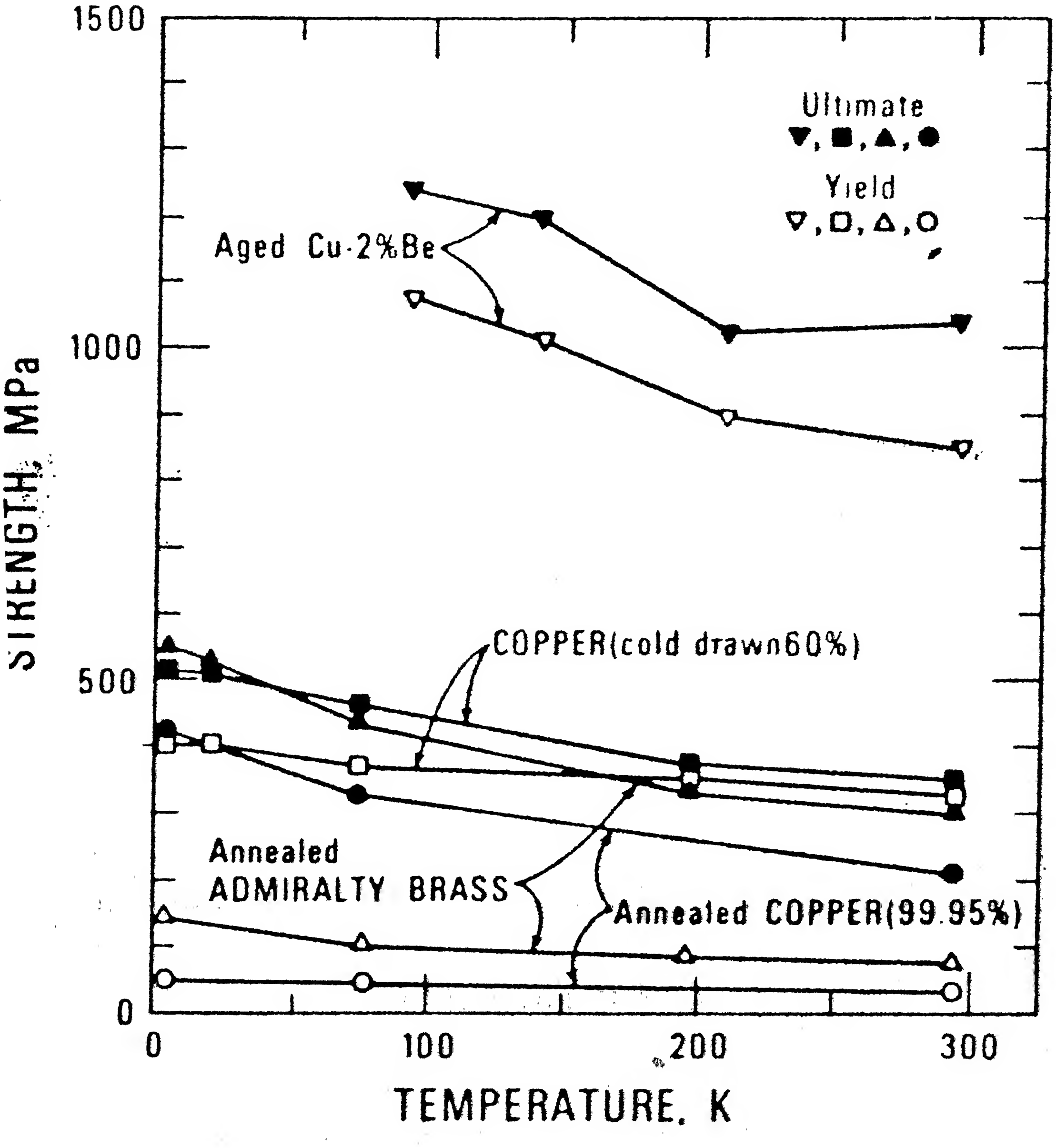


FIG. 2.7: YIELD AND ULTIMATE TENSILE STRENGTHS AS A FUNCTION OF TEMPERATURE FOR COPPER ALLOYS[10].

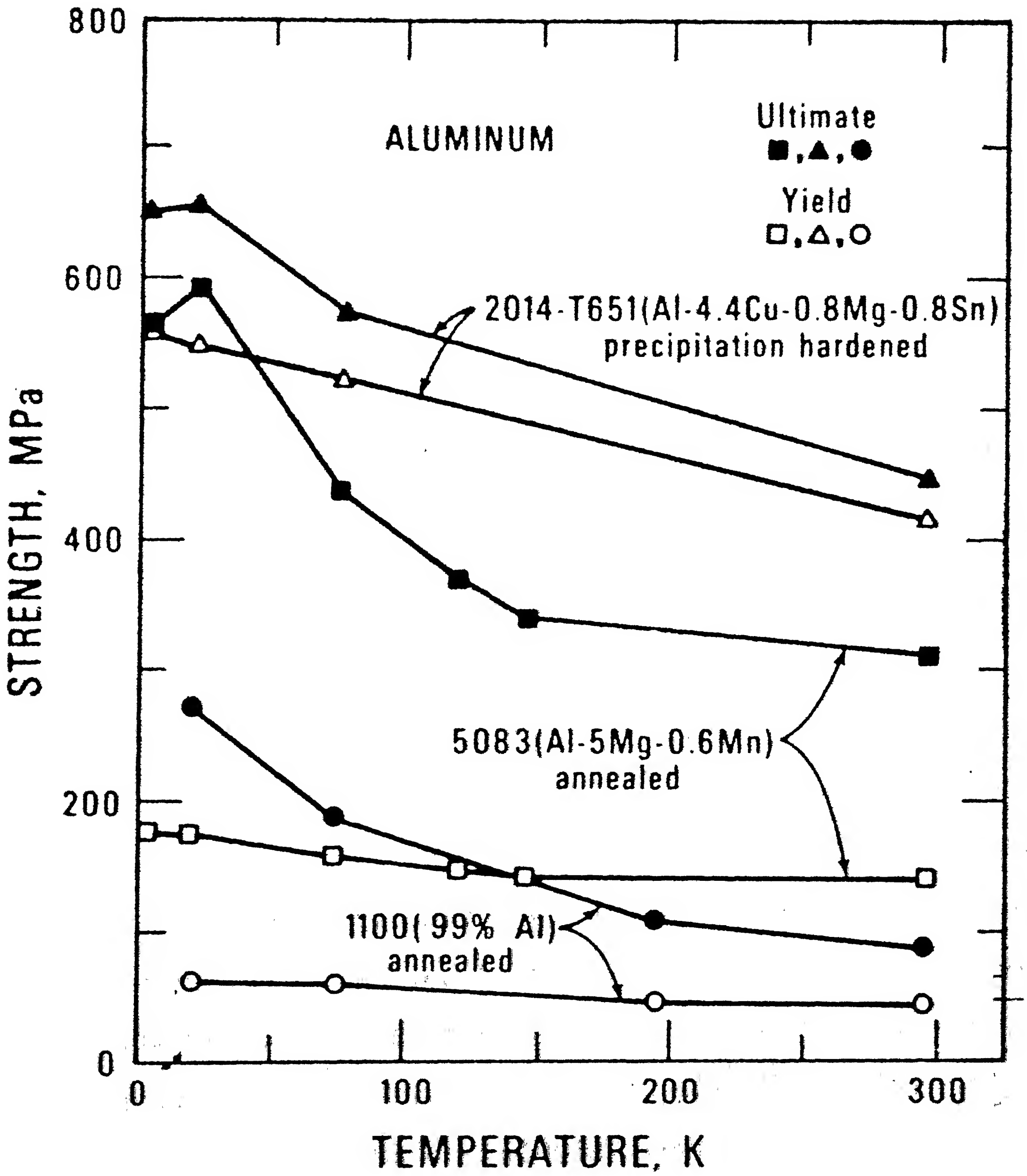


FIG. 2.8: YIELD AND ULTIMATE TENSILE STRENGTHS AS A FUNCTION OF TEMPERATURE FOR ALUMINIUM ALLOYS [10].

in formation of solid solutions and inter metallic compounds. Titanium alloys can be classified into three classes: all alpha alloys, alpha beta alloys, and all beta alloys.

Commercially pure titanium and all alpha titanium alloys have fairly low strengths. They are very ductile and tough at room temperature. Tensile and yield strength are greatly increased at cryogenic temperatures. Due to presence of interstitial ductility and toughness are greatly affected. Very low interstitial grades of titanium retain their ductilit at low temperatures. Normal commercial amount of interstitial adversely affect the ductility of titanium alloy. Toughness of titanium alloy decreases severely below temperature $77^{o}K$. The alpha beta titanium alloys are affected much in the same way as the alpha titanium alloys. However, most of the alpha-beta titanium alloys lose ductility and toughness at 200 to $77^{o}K$.

All beta titanium have very high strength and good weld bility. Beta titanium behaves like bcc materials. As like bcc materials it becomes brittle. Transition temperature for all beta titanium has been found to be at about $200^{o}K$. The rate of increase of tensile strength of titanium alloy exceeds the rat of shear strength on reducing temperature [24]. Fig. 2.9 summarize the mechanical properties of titanium alloys.

(e) <u>Copper and Copper Alloys:</u>

Copper and its alloys have fcc crystalline structures. Yield and tensile strength increase like the other fcc materi

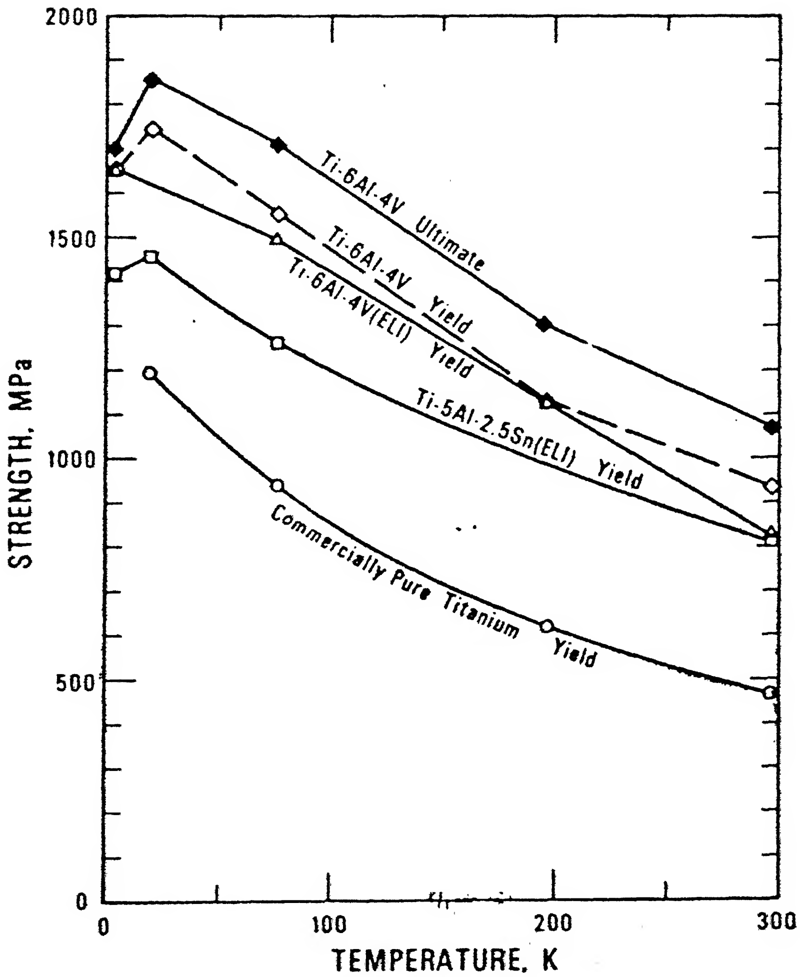


FIG. 2.9: YIELD STRENGTHS AS A FUNCTION OF TEMPERATURE FOR TITANIUM ALLOYS [10].

Copper and its alloys have no effect on their ductility and toughness.

2.5.3 Polymers and Glasses [10]:

(a) Polymers:

Polymers exhibit strikingly varied behaviour depending on the temperature and the time scale of the observation. A classic simple polymer observed for common experimental times of the order of 1 sec. to 1 hour has a glassy region, a rubbery region, and a viscofluid region as the temperature is raised. These behaviours are shown in Fig. 2.10 for an amorphous polymer. The term glassy indicates the similarity observed between the properties of polymers at low temperatures and those of glass. As the temperature is raised, the polymer becomes less brittle, and its strength and moduli begin to drop steadily and significantly. Commonly observed values of T_g (glass transition temperature) are in the range 220 to 370°K. The low temperature strengths of polymers are well below those of the usual structural metal. The temperature dependences of their tensile strength and elongation are usually significant, as in the bcc metals. The tensile strength of various polymers are shown in Fig. 2.11.

(b) Glass:

Glass can be defined as an inorganic product of fusion which has been cooled to a rigid condition without crystallization (Jastrzebski, 1959).

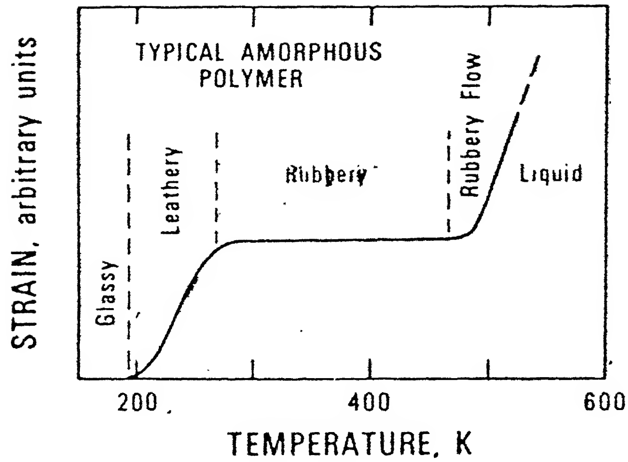


FIG. 2.10: THERMO-MECHANICAL CURVE OF A SIMPLE POLYMER[10].

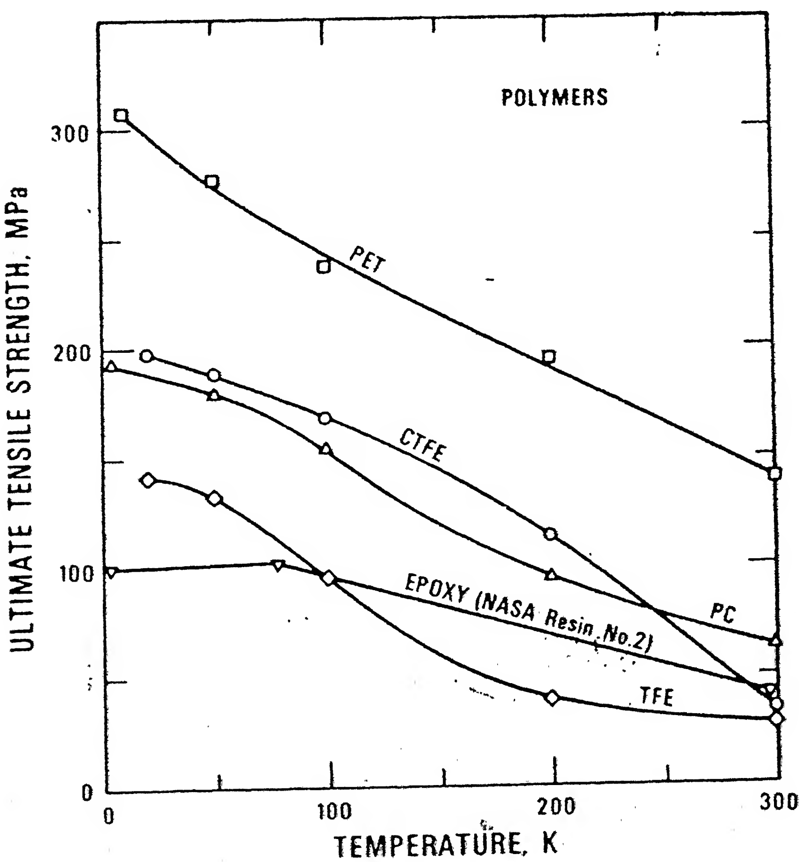


FIG. 2.11: ULTIMATE TENSILE STRENGTHS AS A FUNCTION OF TEMPERATURE FOR POLYMERS[10].

Plastic deformation by dislocation motion is absent. At room temperature and below, however, the viscosity of glass is so high that it behaves as a brittle solid, because no mechanism of plastic deformation on a practical time scale is available.

Kropschot and Mikesell (1957) and Hilling (1961) report increases in the strength of glasses on cooling from room to liquid-nitrogen temperature. Static fatigue is believed to be caused by the growth of pre-existing flows to critical dimensions under the action of a steady stress. Fluctuating stress may also produce flow growth at about the same rate as an equivalent static stress.

2.6 FRACTURE MECHANICS:

Fracture may be defined as the mechanical separation of a solid owing to the application of stress. There are two types of fractures, brittle fracture and ductile fracture. In case of brittle fracture, fracture energy is the energy required to create fracture surfaces. In case of ideal fracture, the energy required for fracture is the simply the intrinsic surface energy of the material [16]. For structural alloys plastic deformation take place before fracture. Due to plastic deformation more energy is required for fracture. Most brittle fractures are initiated by small flows that grow as crack to a critical size. There are three elements to the fracture problem: the initial flow, crack growth, and fracture toughness.

2.6.1 Fracture Toughness:

Fracture occurs when the crake tip stress field reaches a critical magnitude, i.e. when K reaches K_c, the fracture toughness of the material. K_c is a mechanical property that is a function of temperature, loading rate, and micro-structure, much the same as yield strength, however, K_c is also a function of the extent of crack tip plasticity relative to the other specimen (or structural) dimensions [10, 16]. If the plasticity is small compared to the specimen dimensions and the crack size, then K_c approaches a constant minimum value defined as K_{1c}, the plain strain fracture toughness.

2.6.2 Thermal and Metallurgical Effects on Toughness:

Fracture toughness may increase or decrease as temperature is lowered. It depends on the metallurgical factors. Ductile fracture is caused by the formation and growth of the voids. Voids grow, come together and unite by ductile tearing of matrix. Ductile tearing resistance is the function of the strength and ductility of matrix.

Brittle fracture requires less energy for surface formation than ductile fracture.

Fracture toughness of fcc alloy increases between 295 and 4^{o}K. Copper, aluminium, austenitic stainless steels are included in this group.

Mode of fracture for bcc alloys is different from fcc alloys because of their ductile to brittle transition. Fracture of bcc alloys at cryogenic temperatures, occurs as a result of local deformation limited the portion initially deformed [23].

Fracture toughness of hcp materials is usually quite low. Hexagonal close packed materials behave quite similar to bcc materials. Many of the hcp alloys exhibit transitional behaviour. Zink, beryllium, magnesium and titanium come in this group.

Typical fracture toughness data for three types of structural alloys are illustrated in Fig. 2.12. It is clear that fcc structure are toughest material class at cryogenic temperatures. Higher yield strength alloys are less tough. In another words yield strength is inversely proportional to fracture toughness, as shown in Fig. 2.13.

2.6.3 Fracture Toughness of Polymer and Glass [10]:

Linear, elastic fracture toughness tests have been applied to some polymers that experience only small amounts of plastic deformation prior to fracture. The K_{1c} values for plastics are usually less than 10 $MP_a\ m^{1/2}$ at low temperatures. Martine and Gerberich's data for polycarbonate between 325 and 225^oK show a decrease from 4.5 to 2 $MP_a\ m^{1/2}$, but at still lower temperatures (~ 100 K) K_{1c} increases again to 5 $MP_a\ m^{1/2}$. Very little information is available regarding fracture toughness of glass, at low temperatures. Fracture toughness of bcc, hcp and brittle

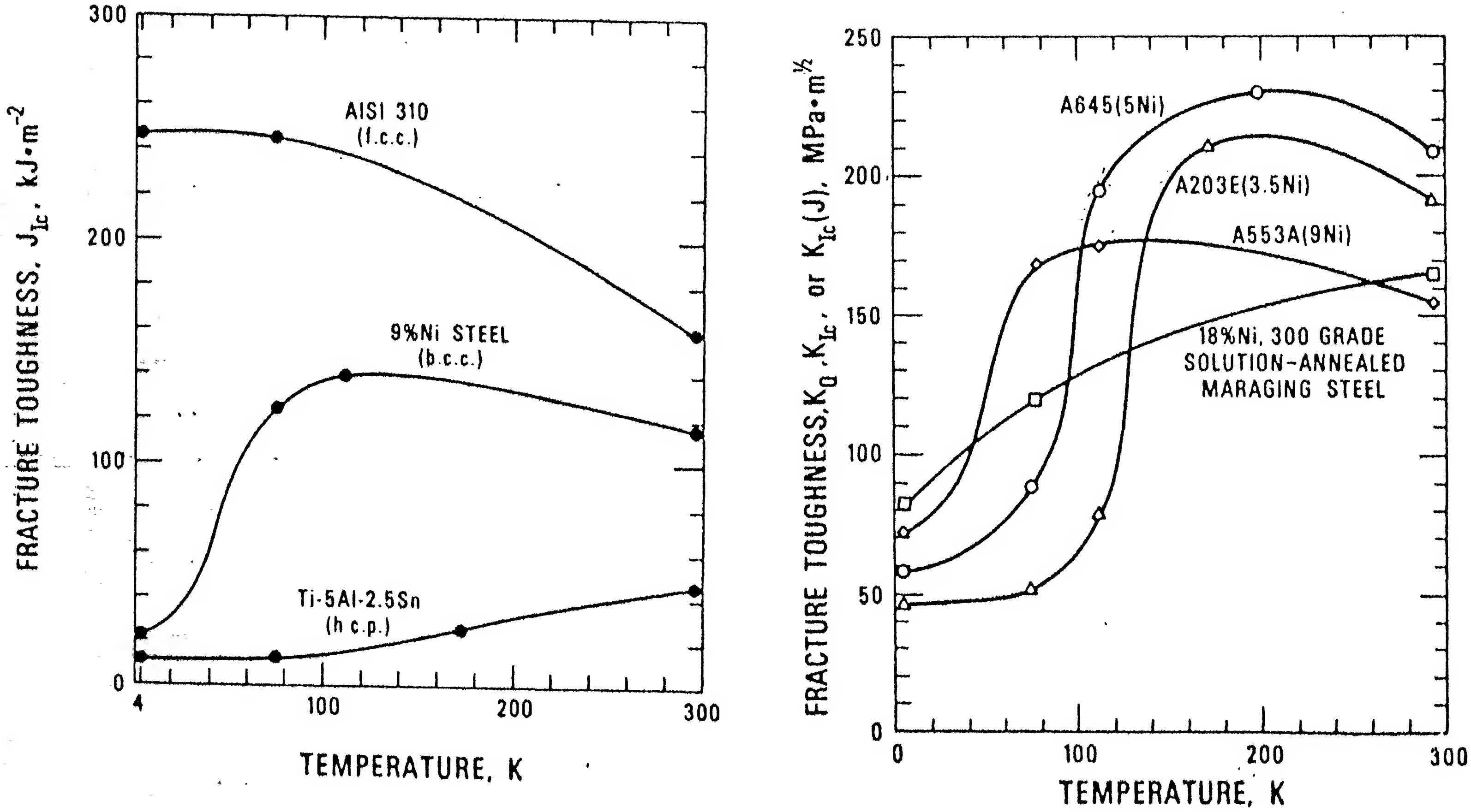


FIG. 2.12: TEMPERATURE DEPENDENCE OF FRACTURE TOUGHNESS FOR ALLOYS [10]

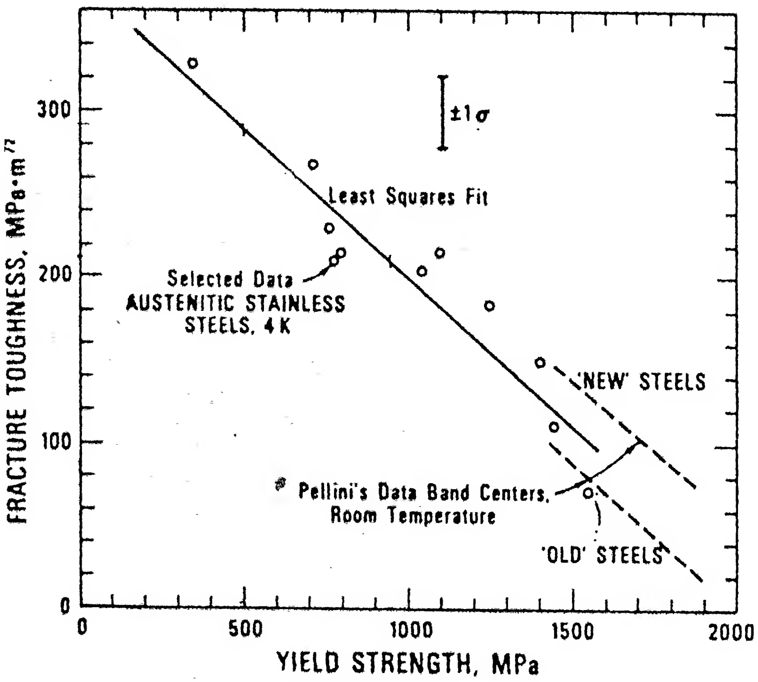


FIG. 2.13(a): STRENGTH VS. TOUGHNESS TREND LINE[10].

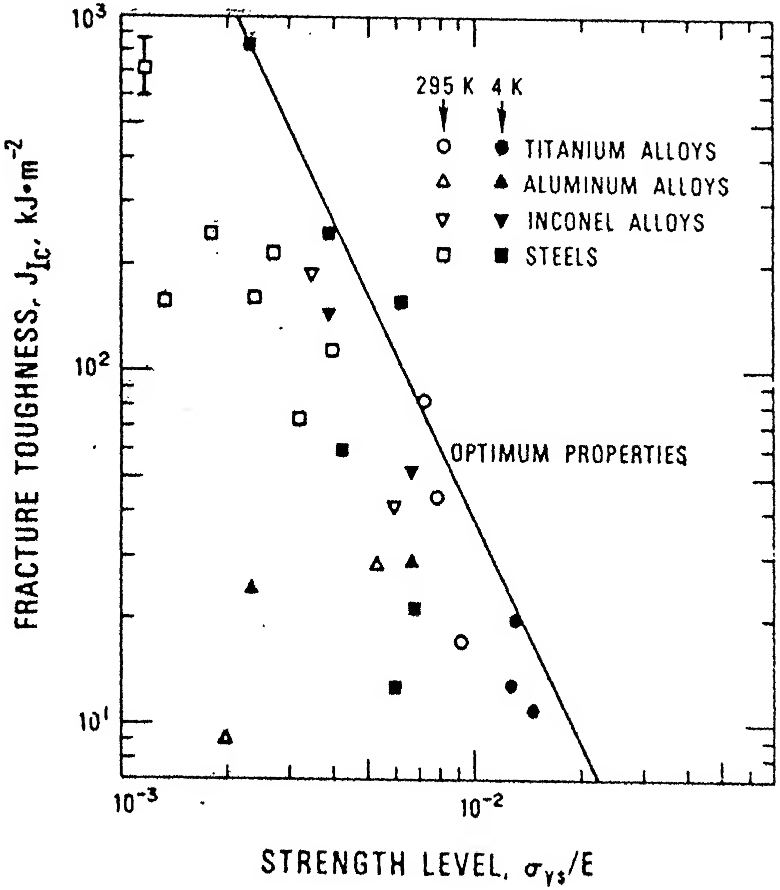


FIG. 2.13(b): FRACTURE TOUGHNESS VS. STRENGTH LEVEL[10]

materials decreases with the increment in strength at low temperatures. From this experimental observation one can deduce fracture toughness of glass will reduce at low temperatures.

2.6.4 Fatigue Strength:

When materials are stressed repeatedly at load below their ultimate tensile strength failure due to fatigue may eventually occur. At cryogenic temperatures, fatigue crack growth rates may be less than at room temperature owing to elevation of the yield strength, which reduces cyclic plasticity. Important exceptions are brittle materials and materials behaving in a brittle manner. The limited number of fatigue failure showed clearly that the fatigue strength of these materials were decreased at temperature below their ductile brittle transition.

CHAPTER III

MACHINING OF MILD STEEL AT LOW TEMPERATURE

3.1 MECHANICS OF METAL CUTTING:

3.1.1 Orthogonal Cutting:

In orthogonal cutting operation the tool edge is straight, it is normal to the direction of cutting, and normal also to the feed direction. On lathe these conditions are secured by using a tool with the cutting edge horizontal, on the centre line, and at right angles to the axis of rotation of the work. Fig. 3.4 shows how these conditions can be achieved on a lathe operation on a pipe. In this method, cutting speed is not quite constant. It is maximum at the outside of the tube and minimum at the inner side of the tube. But if the tube dia. is reasonably large, this is of minor importance. In cutting tube chip can spread in both directions. This is the reason the cross-section of the chip is not strictly rectangular. Usually chip thickness is greatest near the middle, tapering off some what towards the sides. For mathematical simplification, it is usually assumed a rectangular cross-section of chip, whose width is the original depth of cut. For calculation purposes thickness of chip is taken as the mean thickness of the chip.

3.1.2 Heat in Metal Cutting:

The power consumed in metal cutting is largely converted into heat near the cutting edge of the tool. Because of the very large amount of plastic strain, it is unlikely that more than 1% of the work done is stored as elastic energy, the remaining 99% going to heat the chip, the tool and the work material.

The most obvious indication of the temperature of steel chip is seen in its change of colour, usually to a brown or blue, a few seconds after leaving the tool. Temper colours are caused by a thin layer of oxide on the steel surface and indicate a temperature of the order of 250 to 350°C [23]. At very low speeds the chip does not change colour indicating a lower temperature.

3.1.3 Wear and Tool Life:

In almost all machining operations the action of cutting gradually changes the shape of the tool edge so that in time the tool ceased to cut efficiently, or fails completely. Observations have shown that the shape of the tool edge may be changed by plastic deformation as well as by wear. Wear can be described as total loss of weight or mass of the sliding pairs accompanying friction. Wear may be classified into several types as follows:

1. Attritious (small particles) wear associated with adhesion, prow formation, and shear plane ends.

2. Abrasion wear (due to cutting action of hard particles).
3. Erosive wear (cutting action of particles in a fluid).
4. Diffusion wear at high surface temperatures.
5. Corrosive wear (due to chemical attack of a surface).
6. Fracture wear (chipping of brittle surfaces).

Practical wear situations rarely involve only one of these types of wear. Wear phenomenon is very complex and dependent on many aspect, viz. tool work pair, environment, temperature of interfaces etc. Tool work interface temperature plays important role in wear processes. As the temperature increases wear process shifted from abrasion to adhesion or from adhesion to diffusion.

Adhesive Wear:

At low cutting speed the flow of metal past the cutting edge is more irregular and built-up edge may be formed. Metallic surfaces are brought into intimate contact under moderate loads, a metallic bond between adjoining materials takes place. This phenomenon is known as 'adhesion.' These types of bond are usually stronger than the local strength of material, cause the transfer of particle from one surface to other. Under these conditions fragments of microscopic size, may be torn intermittently from the tool surface, and we refer to the mechanism as attrition wear. In this process fragment of grains are pulled away, with some tendency to fracture along the grain boundaries, leaving very uneven worn surface. In continuous

cutting operations using HSS tool, attrition wear is usually in small form. It is not accelerated by high temperature. At high speed as the flow of metal past the cutting edge becomes laminar, attrition wear tends to disappear.

Abrasive Wear:

Abrasive wear involves the loss of material by the formation of chips as in abrasive machining. Abrasive wear of HSS tools requires the presence in the work material of particle harder than the martensitic matrix of the tool. Hard carbides, oxides and nitrides are present in many steels, but there is little direct experimental evidence to indicate whether abrasion by these particles does play an important role in the wear of tool [23]. Abrasion is intuitively considered as a major cause of tool wear.

Diffusion Wear:

Intermetallic diffusion between the tool and work materials has been considered probable when high temperature along with a large degree of deformation and a high rate of strain is prevalent at the tool chip interface [24]. There is metal to metal contact and temperature of 700 to 900^{o}C are high enough for appreciable diffusion to take place. The tool surface is decomposed and the decomposition products diffuse into the surface of the chip. Rate of diffusion increases rapidly with temperature, the rate typically doubling for an

increment of the order of 20^{o}C [23].

Fig. 3.1 summarises the discussion of the wear and deformation processes which have been shown to change the shape of the tool and to affect tool life when cutting with HSS. The relative importance of these processes depends on many factors – the work material, the machining operation, cutting condition, tool geometry and use of lubricant.

3.1.4 Coolant and Lubrication:

Coolant and lubricant are used for a number of objectives:

1. To prevent the tool, work piece and machine from over heating.
2. To increase tool life.
3. To improve surface finish.
4. To help clear the swarf from the cutting area.

There are many applications where cutting is carried out in air with no advantage being found in the use of a cutting fluid. For example, many turning and facing operations using carbide or ceramic tools are carried out dry. Single point turning, planing, and shaping and drilling of shallow holes are among the operations where simple water-based coolants may be the only fluid required.

Water based coolants reduce the temperature both of the work piece and of the chip after it has left the tool. The coolant cannot act directly on the thin zone which is the heat

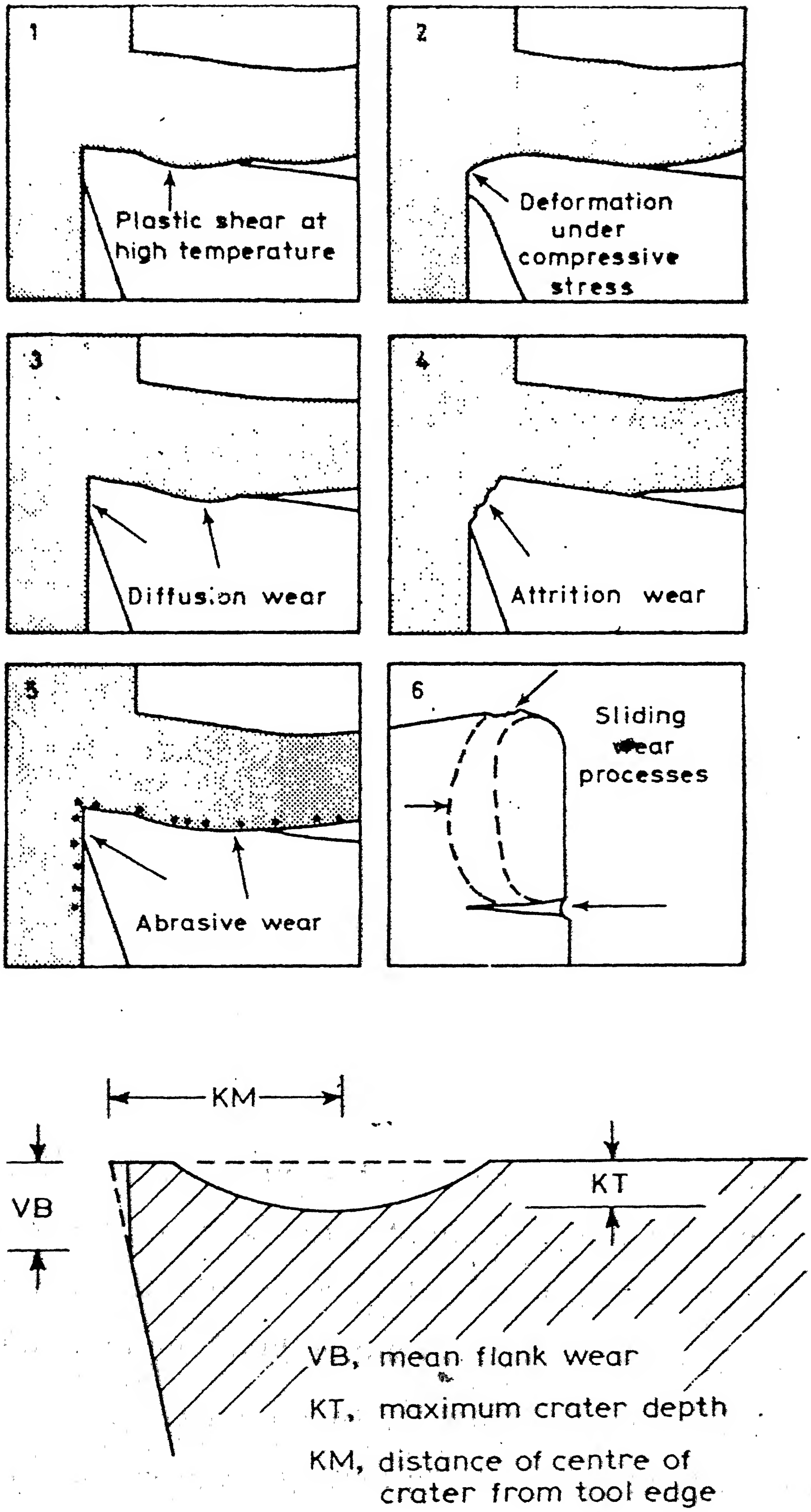


FIG. 3.1: WEAR MECHANISMS ON HIGH SPEED STEEL TOOLS [23].

source but only by removing heat from those surfaces of the chip, the work piece, and the tool which are accessible to the coolant and as near as possible to the heat source. Conduction has no effect on the contact area because very little time for heat to be conducted from the source. The coolant application was unable to prevent high temperature at the tool/work interface, since heat continues to be generated in the flow-zone which is inaccessible to direct action by the coolant. Temperature over 900°C are generated at the hottest part of rake-face of the tool whether cutting dry, flooded with coolant, or with a jet directed at the end clearance face.

Coolant are most likely to be effective in prolonging tool life or permitting a higher rate of metal removal where deformation of the cutting edge is responsible for initial wear and failure. A plentiful supply of water flooded over the tool at low speeds employed was successful in cooling the tool edge sufficiently to permit a significantly higher cutting speed.

With HSS and cemented carbide tools, used at much higher speeds, wear mechanism other than tool edge deformation are more often responsible for tool wear and failure, but coolants still have a significant effect.

In continuous turning of steel with HSS tools the rate of flank wear may be greatly increased by use of water base cutting fluids when compared with dry cutting [3,23].Under some test

conditions the rate of flank wear was accelerated by a factor of five or more. This particularly occured at low feed, and despite the fact the tool temperature lowered by the use of water (Fig. 3.2).

Understanding of the action of coolant and lubricants in metal cutting is still at a rather primitive level. The conditions are very complex and practical men will wisely continue to rely on practical tests in development and selection of cutting fluids.

Action of Coolant and its Effect on Tool Life:

From the above discussion one can deduce that effect of conventional coolant is not always positive. In almost all cases it reduces the interface temperature but fails to increase tool life in many cases. This is a very strange result opposite to the theoretical expectation. To explain this action of coolant many researchers have given their explanations. From practical observation centre of the crater is found to be closer to the tool point. It indicates that even though the water carries some heat away from the wear land, it simultaneously shift the maximum temperature closer to the tool tip. Maximum temperature closer to the tip means more heat will flow into the wear land. At higher cutting speed coolant get little time to reduce the temperature of deformation zone. Due to sticking type of friction it also have little effect on chip-tool interface temperature. Mainly coolant reduce the temperature of

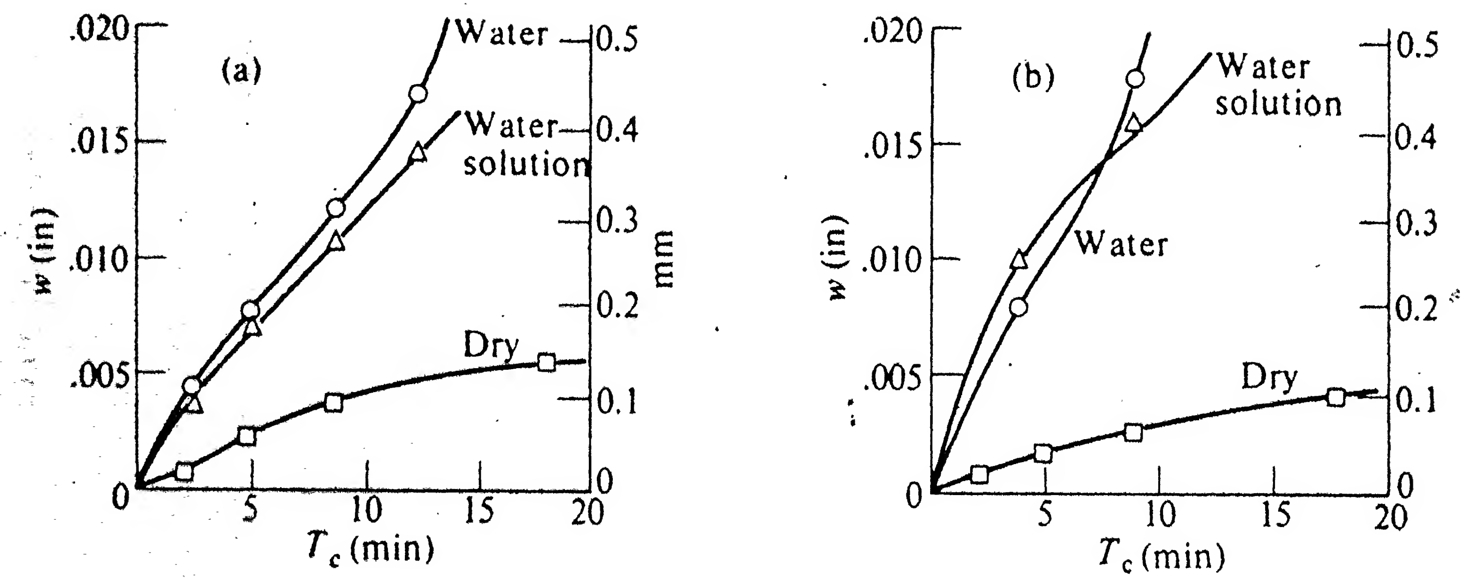


FIG. 3.2: VARIATION OF WEAR LAND (W) WITH CUTTING TIME T_c FOR DIFFERENT CUTTING FLUIDS [3]

(a) AISI 1020 STEEL MACHINED WITH HSS TOOL.

(b) AISI 4340 STEEL MACHINED WITH HSS TOOL.

chips, work-piece and overall temperature of tool. But temperature of wear zone experience little effect of coolant. Shifting of maximum temperature zone and inefficient cooling affect, raise the tool wear in most of the cases.

3.2 EXPERIMENTAL PROCEDURE OF FORCE MEASUREMENT:

Calibration of Dynamometer:

Before starting the experiment, dynamometer was calibrated using constant dead weight. Calibration was done for both the forces, cutting force and feed force. On the basis of load and corresponding deflection (inform of mv) obtained by recorder a calibration chart was prepared. Calibration chart is a load vs. deflection graph (Fig. 3.3). A straight line was found to fit the data. Now, from this calibration chart the unknown force can be read knowing the deflection of the recorder.

Experimental Set-up for Cooling Arrangement:

One fully filled liquid nitrogen container of 26 litre was taken. Experimental set-up is shown in Fig. 3.4. Air under a pressure of 2 kg/cm^2 sent on the surface of liquid nitrogen, liquid could come out in form of a jet. This liquid nitrogen jet was applied on the face of the pipe ahead of the cutting zone for colling purpose, as shown in Fig. 3.4.

Procedure:

To perform the orthogonal cutting operation a m.s. pipe of 152 mm internal dia was taken. Its wall thickness was reduced

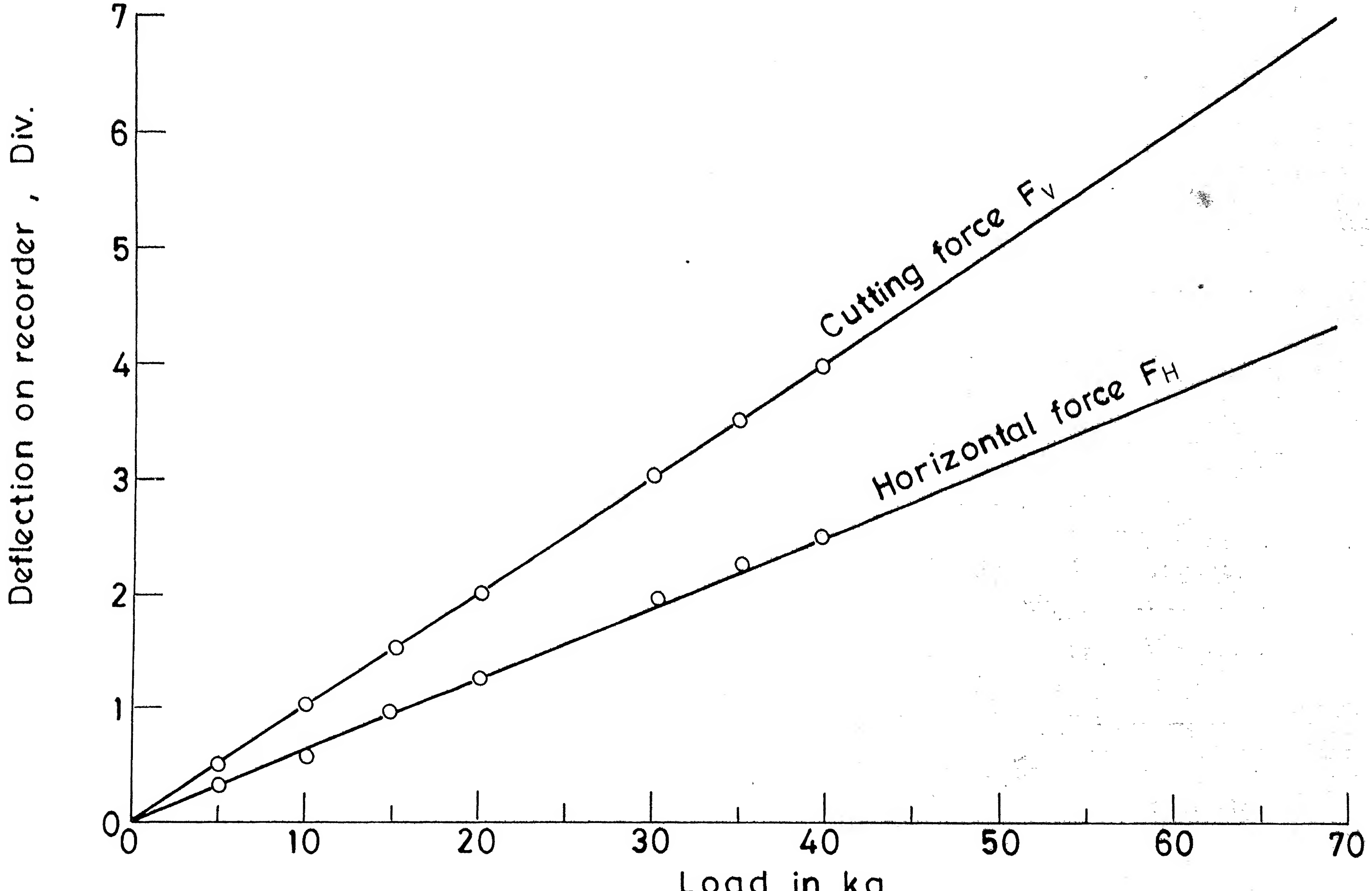


Fig. 3.3 Dynamometer calibration curve. Input voltage -5V. Sensitivity of record 0.01 V full scale.

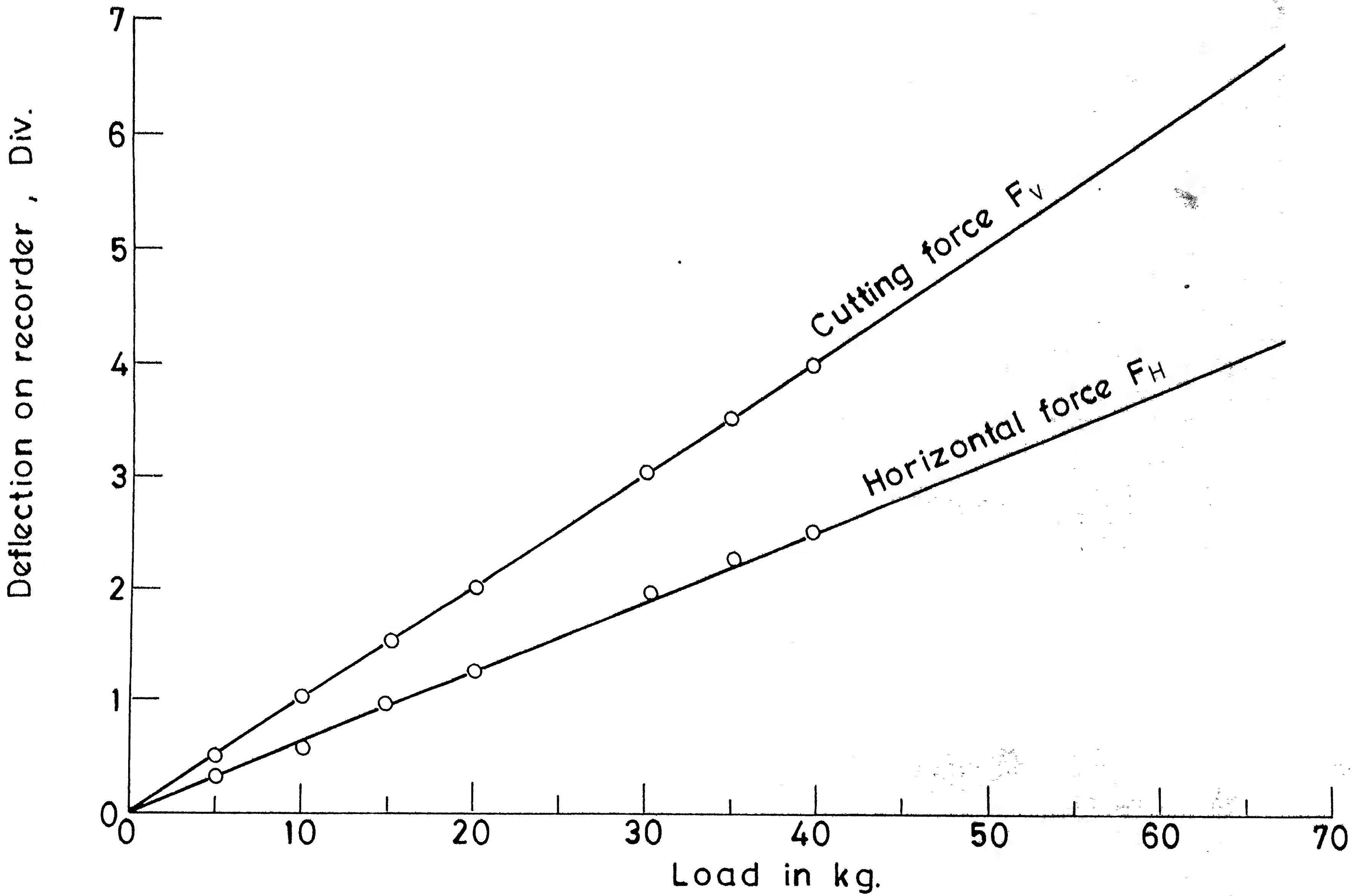


Fig. 3.3 Dynamometer calibration curve. Input voltage -5V. Sensitivity of recorder 0.01 V full scale.

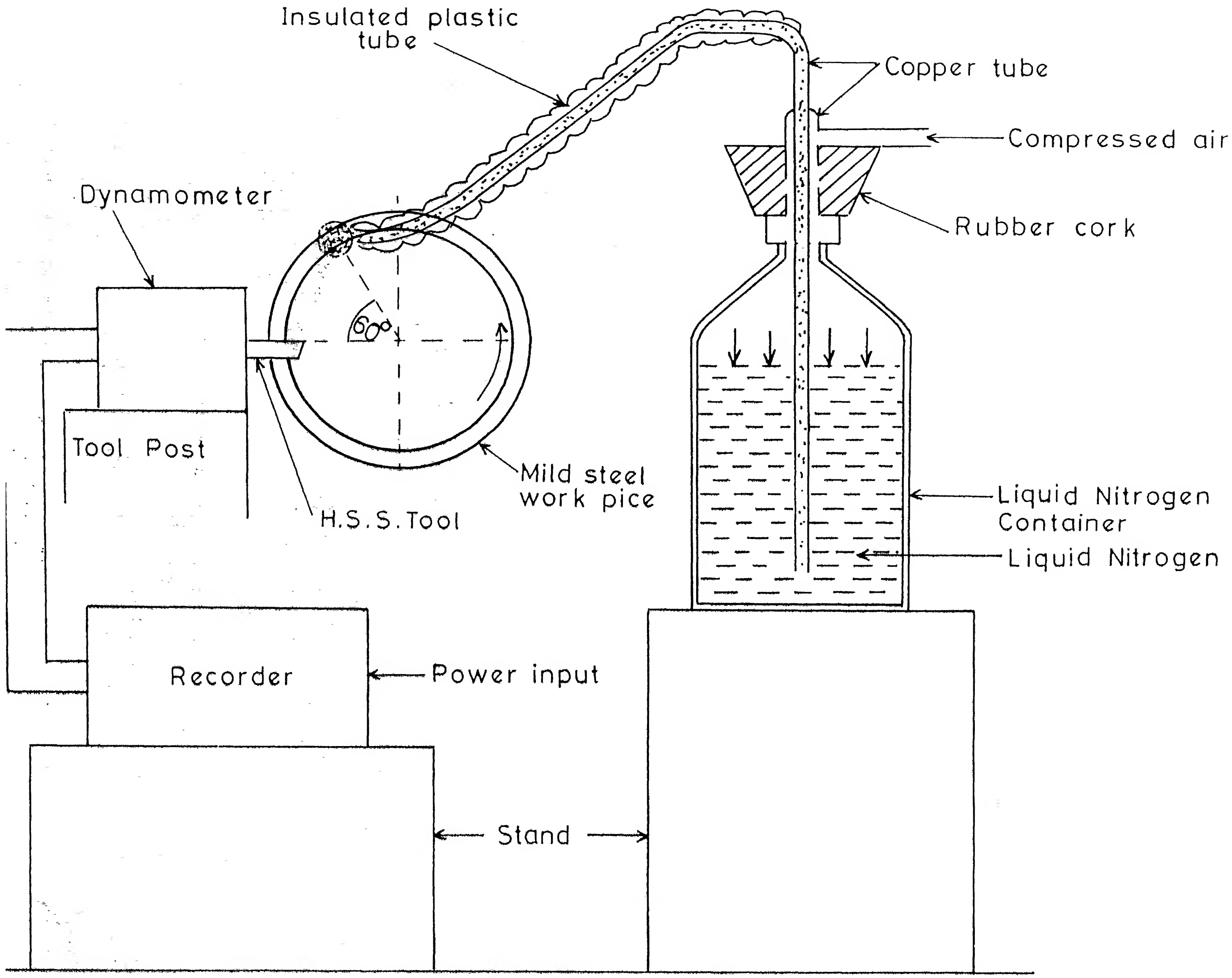


Fig.3.4 Schematic diagram for force measurement.

to a constant wall thickness of 2.6 mm by turning and boaring operations. One HSS tool of appropriate length and proper geometry (back rake 0^o, side rake 15^o, and side clearance 7^o) was fastened to the dynamometer for force measurement. Dynamometer connected to the double channel omniscribe recorder, directly recorded the two components of forces on the graph paper. Cutting operation was continued till recorder system indicated a stable deflection. Cutting operations were performed at three different speeds and cutting forces were recorded for corresponding speeds. This experiment was repeated for three cutting conditions. First dry condition, second using simple water as a coolant and third using liquid nitrogen as a cooling agent. In each case shear plane angle was evaluated. In case of liquid nitrogen condition however, discontinuous chips were not obtained. This was obviously against the expectation. Bright, straight and continuous chips were obtained rather than discontinuous chips. All the experimental and calculated results are tabulated in the Table Nos. 3.1 and 3.2 and plotted in Fig. 3.5, 3.6 and 3.7.

3.2.1 Result and Discussion:

Cutting Forces:

From the experimental results it is clear that the cutting forces are almost independent of cutting velocity. Actually cutting forces get affected by the shear plane angle. As the shear plane angle increases shear plane area decreases, hence

tool has to over come less plastic deformation resistance. Cutting forces also depend upon the chip contact length and nature of chip. Again, chip contact length is a function of shear angle and can be expressed in the following form:

$$C_p = a_2 \left[1 + \tan(\beta - \gamma)\right]$$

C_p - Chip contact length

a_2 - Chip thickness

β - Shear angle

γ - Rake angle.

Cutting forces were decreased significantly when using water as a coolant or liquid nitrogen as a cooling agent. There is not much difference between affects of water and liquid nitrogen on the cutting forces. Comparatively, however, liquid nitrogen has better affect on the cutting forces.

Coefficient of Friction (μ):

In both the cases coefficient of friction got reduced. But reduction in coefficient of friction in case of water is more than that of liquid nitrogen. This result indicates that water has more lubricating effect than liquid nitrogen.

In all the cutting cases, the magnitude of the coefficient of friction was found much more than the conventional sliding coefficient of friction. The explanation can be given in this manner. The values of μ tabulated in the Table No. 3.1 were

Table 3.1

Mean work piece dia - 159.3 mm
Feed - 0.05 mm/rev
P_z - cutting force
F - friction force
F = $P_z \sin\gamma + P_x \cos\gamma$
Coefficient of friction μ = F/N

Width of cut - 2.6 mm
Rake angle (γ) - 15^o
P_x - feed force
N - normal force
N = $P_z \cos\gamma - P_x \sin\gamma$
Friction angle η = $\tan^{-1}\mu$

Speed m/min	Cutting condition	P_z kg	P_x kg	F kg	N kg	μ	η^o
40	Dry	62.67	55	69.35	46.3	1.5	56.31
62.6	Dry	64.67	61	75.66	46.68	1.62	58.31
80.1	Dry	59.67	58.33	71.79	42.34	1.7	59.53
40	Water	45.67	31.33	42.08	36	1.17	49.48
62.6	Water	43.67	33	43.18	33.64	1.28	52.00
80.1	Water	45.67	35.33	45.95	34.97	1.31	52.64
40	Liquid N_2	45	33.86	44.35	34.70	1.28	52.00
62.6	Liquid N_2	45	37.28	47.65	33.82	1.41	54.65
80.1	Liquid N_2	43	38.14	47.97	31.66	1.52	56.66

Table 3.2

Work material - Mild Steel

Mean work piece dia. - 159.3 mm

Feed (a_1) = 0.05 mm/rev

(a_2) = Chip thickness

β - Shear angle

$$\tan\beta = \frac{\cos\gamma}{\xi - \sin\gamma}$$

Tool Material - H.S.S.

Width of cut - 2.6 mm

Rake angle (γ) = 15°,

Side clearance (α) = 7°

ξ - Chip reduction coefficient

$= a_2/a_1$

Speed m/min.	Cutting condition	a_2 mm	$a_2/a_1 = \xi$	β_1	β_2	β_3
40	Dry	0.271	5.42	10.6	3.69	24.34
62.6	Dry	0.276	5.52	10.4	1.69	22.34
80.1	Dry	0.280	5.6	10.25	0.47	22.73
100.1	Dry	0.266	5.32	10.8	—	—
40	Water	0.188	3.76	15.42	10.52	27.76
62.6	Water	0.191	3.82	15.17	8.0	26.5
80.1	Water	0.195	3.9	14.87	7.36	26.18
100.1	Water	0.186	3.72	15.6	—	—
40	Liquid N_2	0.186	3.72	15.6	8.0	26.5
62.6	Liquid N_2	0.187	3.74	15.51	5.35	25.17
80.1	Liquid N_2	0.193	3.86	15.01	3.34	24.17
100.1	Liquid N_2	0.180	3.6	16.12	—	—

β_1 = Experimental shear angle

β_2 = Lee and shaffer shear angle

β_3 = Ernst and Merchant shear angle

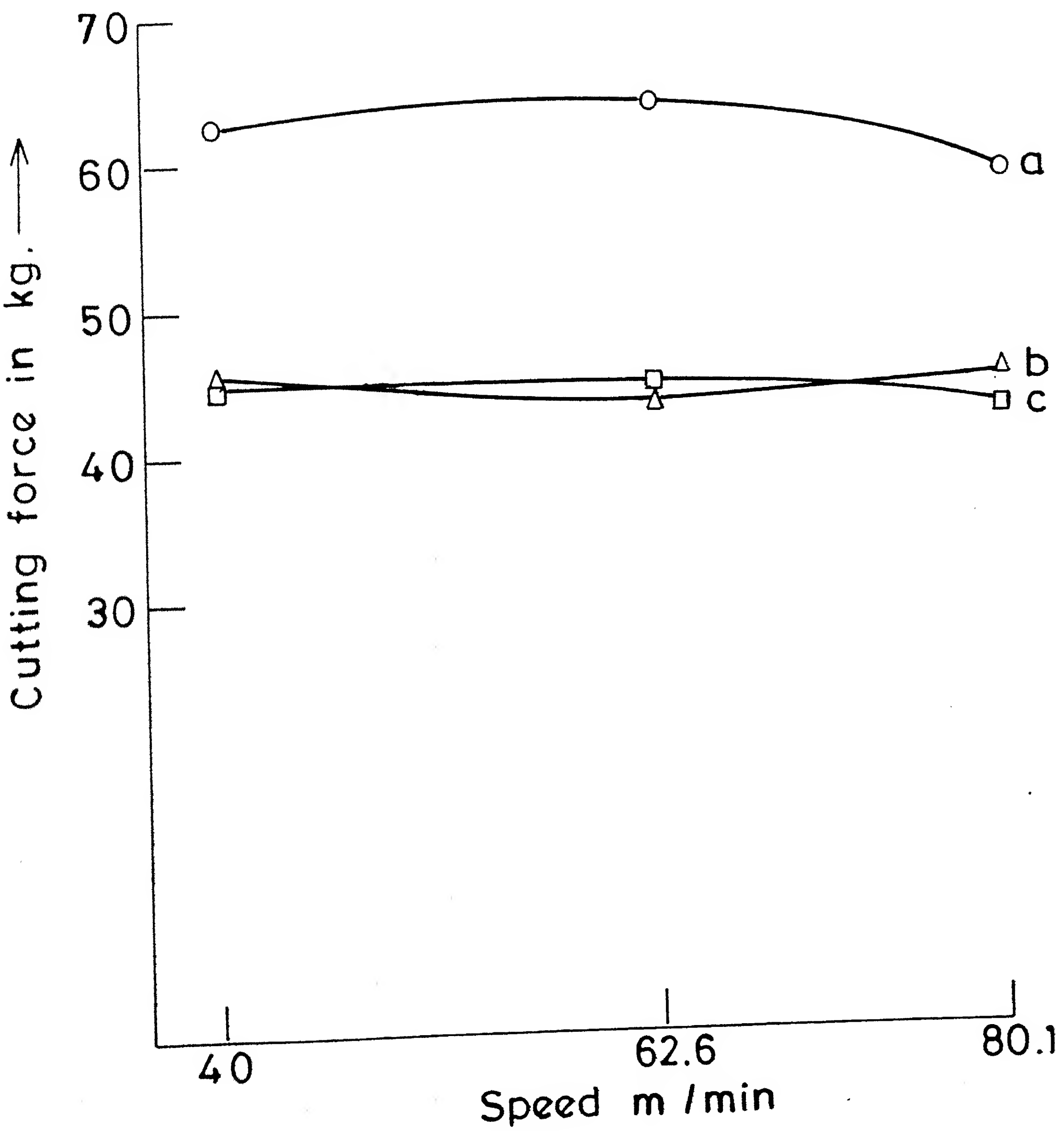


Fig. 3.5 Comparison of cutting force.
(a) Dry cutting. (b) Water as a coolant.
(c) Liquid nitrogen condition.
feed - 0.05 mm / reV, depth of cut - 2.6 mm.

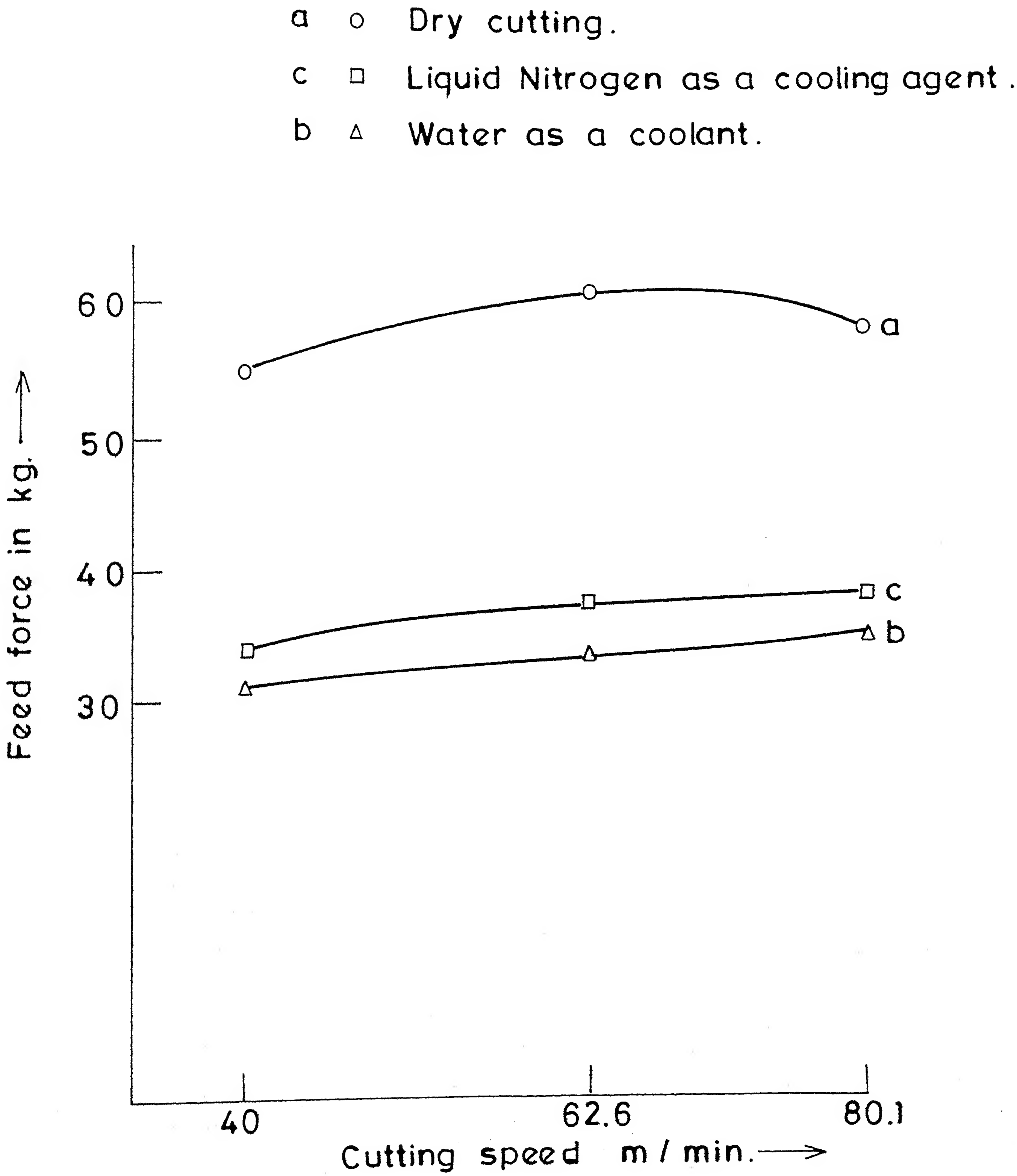


Fig. 3.6 Comparison of feed force.
feed - 0.05 mm/rev, depth of cut 2.6 mm.

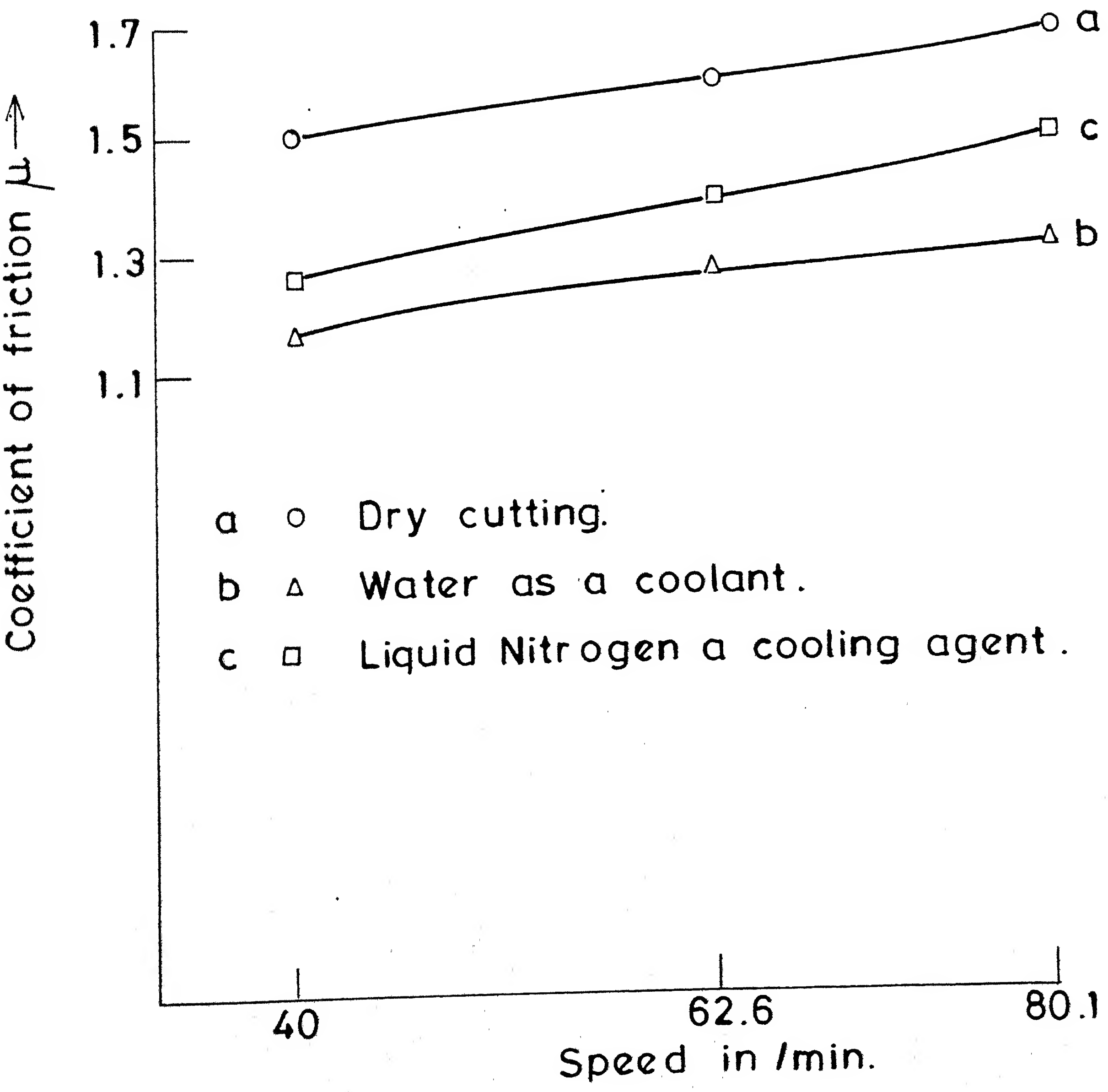


Fig. 3.7 Comparison of coefficient of friction (μ) feed - 0.05 mm, depth of cut - 2.6 mm.

calculated by classical approach of the friction. But classical approach of friction cannot be applied in the metal cutting process because of the following reasons.

(i) There can be no simple relationship between the forces normal to and parallel to the tool surface.

(ii) The force parallel to the tool surface is not independent of the area of contact, but on the contrary, the area of contact between tool and work is a very important parameter in metal cutting.

When the normal force is increased to such an extent that the real area of contact is a large proportion of the apparent contact area, it is no longer possible for the real contact area to increase proportionately to the load. In the extreme case, where the two surfaces are completely in contact, the frictional force becomes that required to shear the material across the whole interface. It is therefore, important to know what conditions exist at the interface between tool and work material during cutting. According to Trent [23] contact between tool and work surface is so nearly complete over a large part of the tool area of the interface, the sliding at the interface is impossible under most cutting conditions.

3.3 EXPERIMENTAL PROCEDURE OF TEMPERATURE MEASUREMENT:

Principle:

The most extensively used method of tool temperature measurement use the tool and work material as the two elements of thermocouple.

The laws of thermoelectric circuits that are applicable here may be summarized as follows:

1. The emf in a thermoelectric circuit depends only on the difference in temperature between the hot and cold junctions, and is independent of the gradients in the parts making up the system.

2. The emf generated is independent of the size and resistance of the conductors.

3. If the junction of two metals is at uniform temperature, the emf generated is not affected if a third metal, which is at the same temperature, is used to make the junction between the first two.

Application of these principle in practice is illustrated in Fig. 3.8. For this purpose long HSS tool was taken and a connecting copper wire was soldered to make the connection. One mild steel strip was welded to the end of the work piece (in form of pipe) and it was tapped in the centre of the rotation. One threaded mild steel long rod was connected to the strip. One copper disc was mounted on the next end of the rod and to make

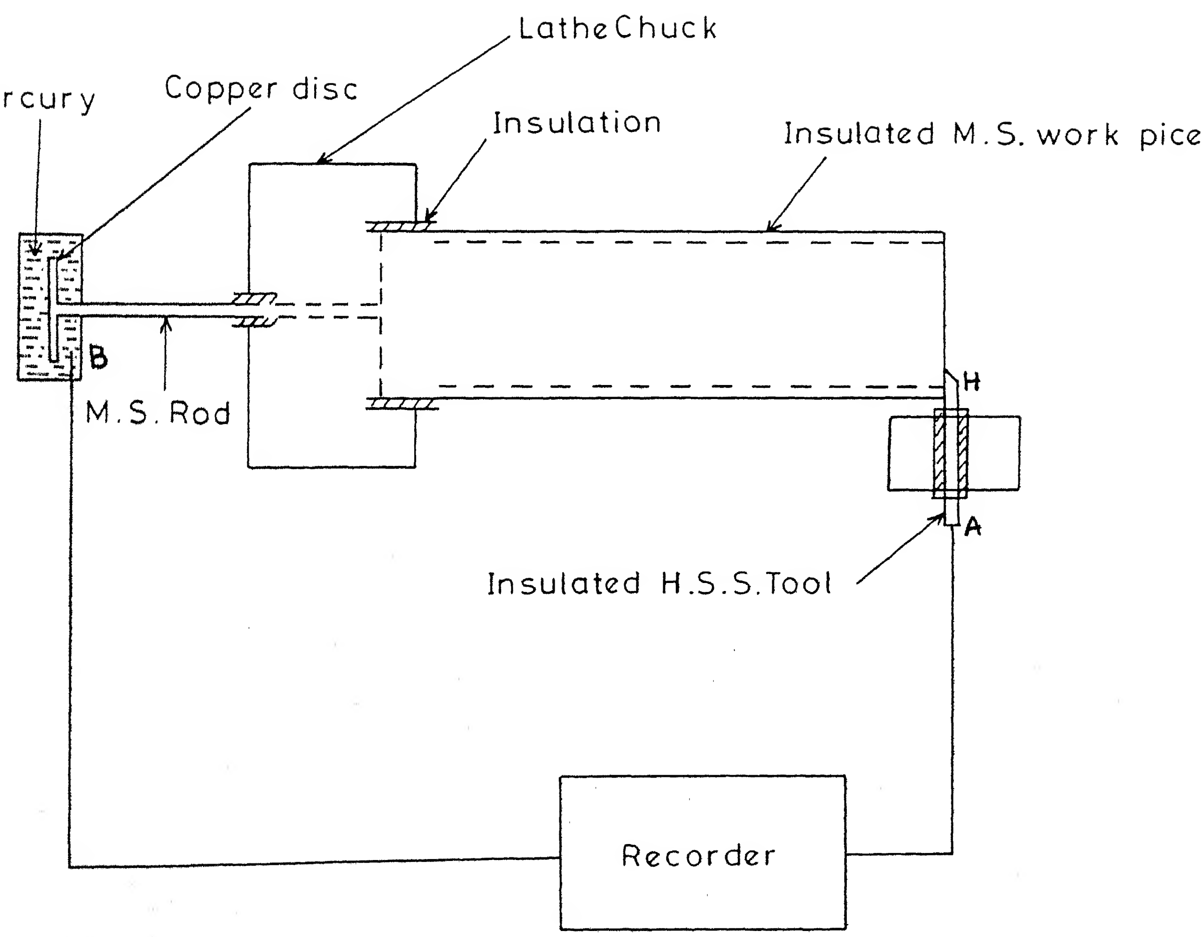


Fig.3.8 Schematic diagram for measuring chip-tool interface temperature.

continuous contact copper disc was kept in the mercury bath. When the work was rotated in turning operation copper disc and mercury bath kept continuous contact. Cutting tool and work piece were electrically insulated from the lathe machine. Omniscribe recorder was used to record the emf generated in the operation. The chip and tool junction H constitutes the hot junction, while A and B, the cold junctions, remain at room temperature.

Experiment was first conducted in dry condition and emf output was recorded for various cutting speeds. Same experiment was repeated using water as a coolant and then liquid nitrogen as a cooling agent. All the emf values were converted into temperature rise values using thermocouple calibration curve shown in Fig. 3.9. Fig. 3.10 compares the value of temperature rise in all the three cutting conditions.

3.3.1 Result and Discussion:

Fig. 3.9 shows the cutting temperature is reduced when using water or liquid nitrogen for cooling purpose. Effect of liquid nitrogen is more significant in lower and higher speed regions. It has been found that water as a coolant become ineffective in higher speed regions [3]. Rise in temperature is the main barrier for high speed cutting. But the present experimental results reveal that high speed cutting is possible using liquid nitrogen as a cooling agent. When liquid nitrogen was used it cooled the work piece to a very low temperature before

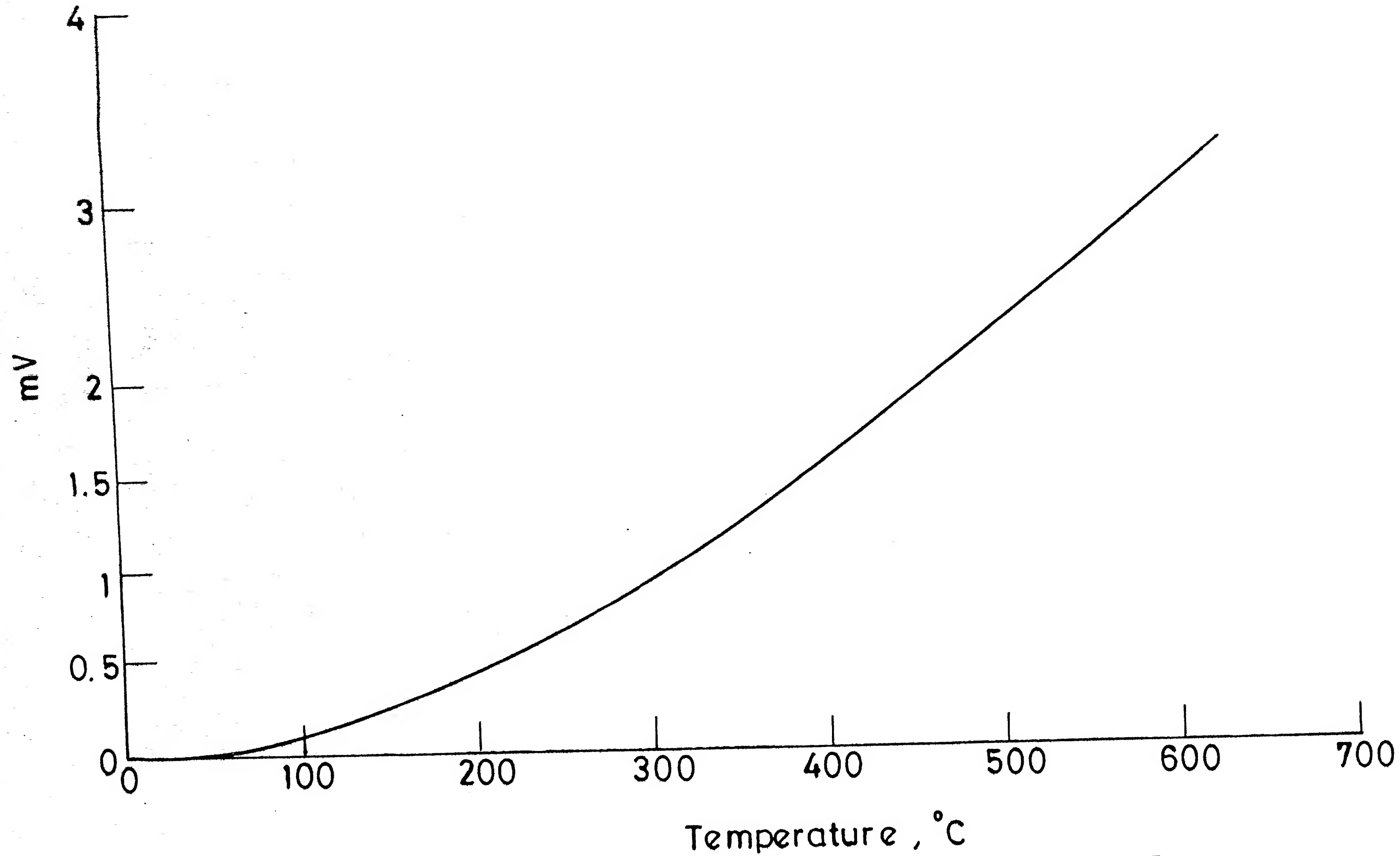


Fig.3.9 Temperature calibration curve of m.s. against HSS [3] .

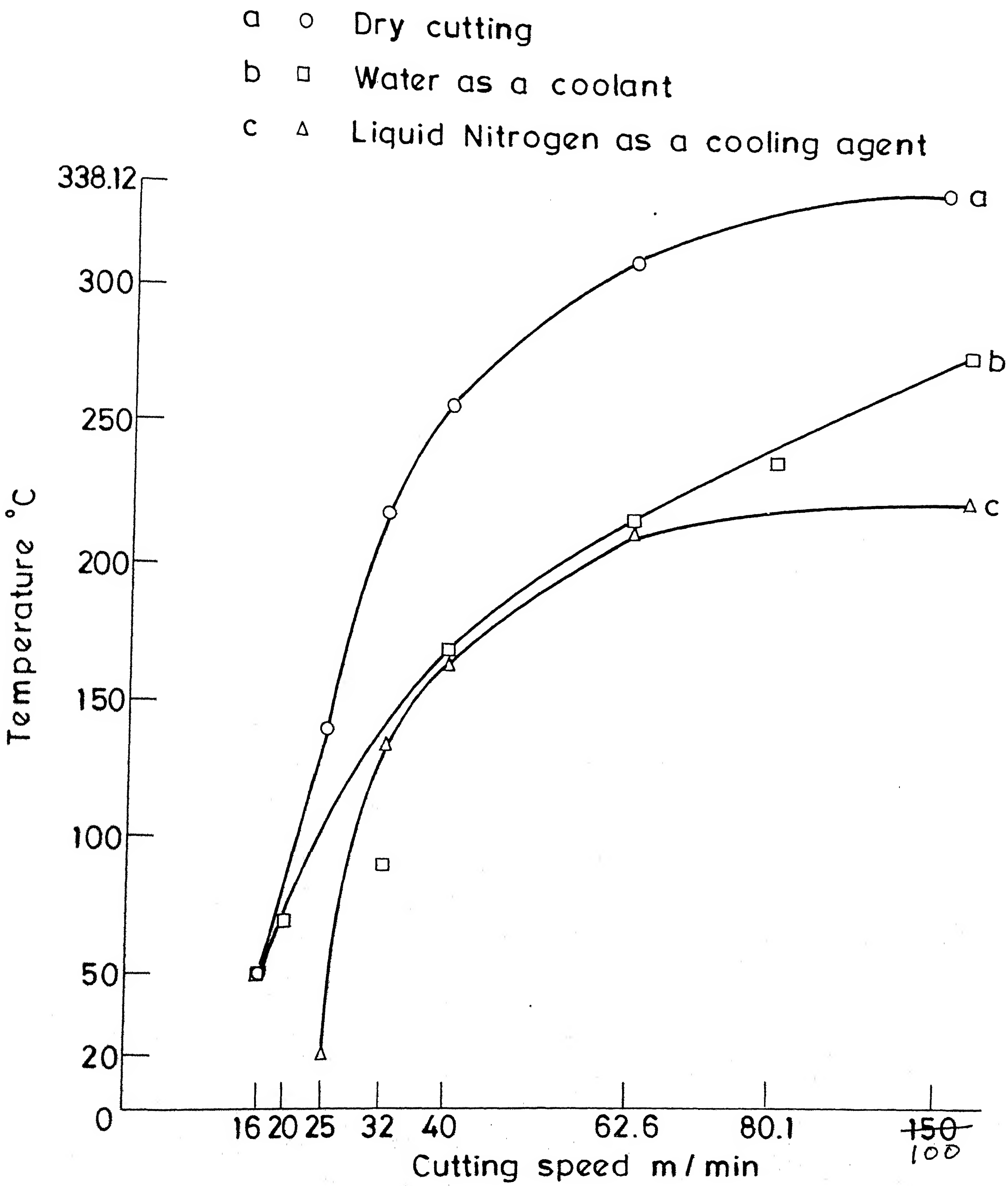


Fig. 3.10 Comparison of chip-tool interface temperature.

Tool - HSS, W.P.- M.S.

Depth of cut - 3 mm, feed - 0.05 mm / rev

the cutting operation. Temperature was depressed to such an extent that much heat was consumed in raising the temperature above the room temperature. However, since experiment was conducted on large size work piece. The temperature decrease was found to be less than expected. It indicates that much heat was being conducted from the other part of the work piece and from the atmosphere.

Experimental works of various workers have indicated that cutting temperature increases with cutting speed. However, cutting forces acting on the tool decrease as the cutting speed is increased. Hence, there is no reason to think that the stresses on the tool increase with cutting speed. The most important heat source responsible for raising the temperature of the tool has been identified as the flow zone where the chip is seized to the rake face of the tool. The amount of heat required to raise the temperature of very thin flow-zone may represent only a small fraction of the total energy expended in cutting. Therefore, there is no direct relationship between cutting forces and the temperature near the cutting edge.

There are several sources of error in the use of this present method. The tool and work material are not ideal elements of a thermocouple. The emf tends to be low and the shape of the emf-temperature curve to be far from a straight line. It is doubtful whether the thermo-emf from a stationary couple, used in calibration, corresponds exactly to that of the same couple during cutting when the work material is being severely strained.

3.4 EFFECT OF LIQUID NITROGEN ON TOOL WEAR AND CHIP DEFORMATION:

3.4.1 Tool Wear:

Figs. 3.11 and 3.12 compare the effect of dry cutting condition and liquid nitrogen cutting condition on wear growth of HSS tool with cutting time. Flank wear was dramatically decreased when using liquid nitrogen as a coolant. Rate of flank wear was more affected at 100 m/min. than the 62.5 m/min.

Significant increase in tool life can be explained as follows. Nitrogen is almost a neutral gas. When liquid nitrogen jet was directed towards the workpiece it was vaporized after the striking the workpiece. Newly vaporized nitrogen displaces the air from the cutting zone and create a almost neutral atmosphere surrounding the cutting zone. At high temperatures tendency of oxidation of tool increases when it comes in contact with oxygen. Nitrogen surrounding retards the oxidation process hence increases the tool life. Boiling point of liquid nitrogen is 77^{o}K. Liquid nitrogen jet was directed onto the work piece at 60^{o} ahead from the cutting point. It reduces the work piece temperature drastically before cutting. Hence much heat generated in the cutting operation was consumed in raising the temperature from low level to a higher. Experimental results shows that tool chip interface temperature was reduced significantly when using liquid nitrogen. Tool life is greatly dependent on the tool temperature. Approximate relation can be given as

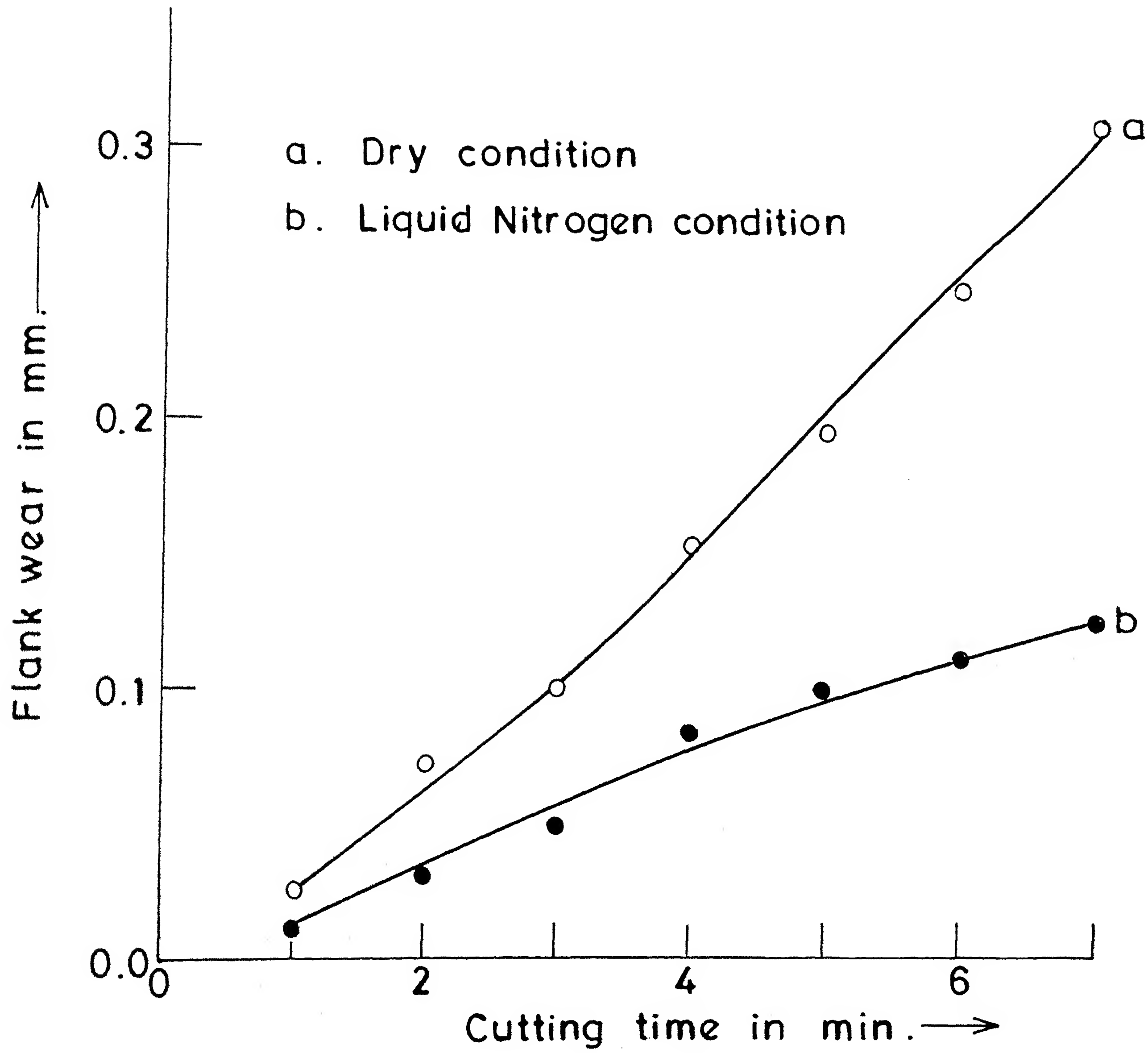


Fig. 3.11 Comparison of growth of flank wear.
Tool - HSS, work material - M.S.
Speed - 68.28 m / min.
Width of cut - 3 mm, feed - 0.05 mm / rev
Side rake - 15°, Side clearance - 7°

a. Dry condition

b. Liquid Nitrogen condition

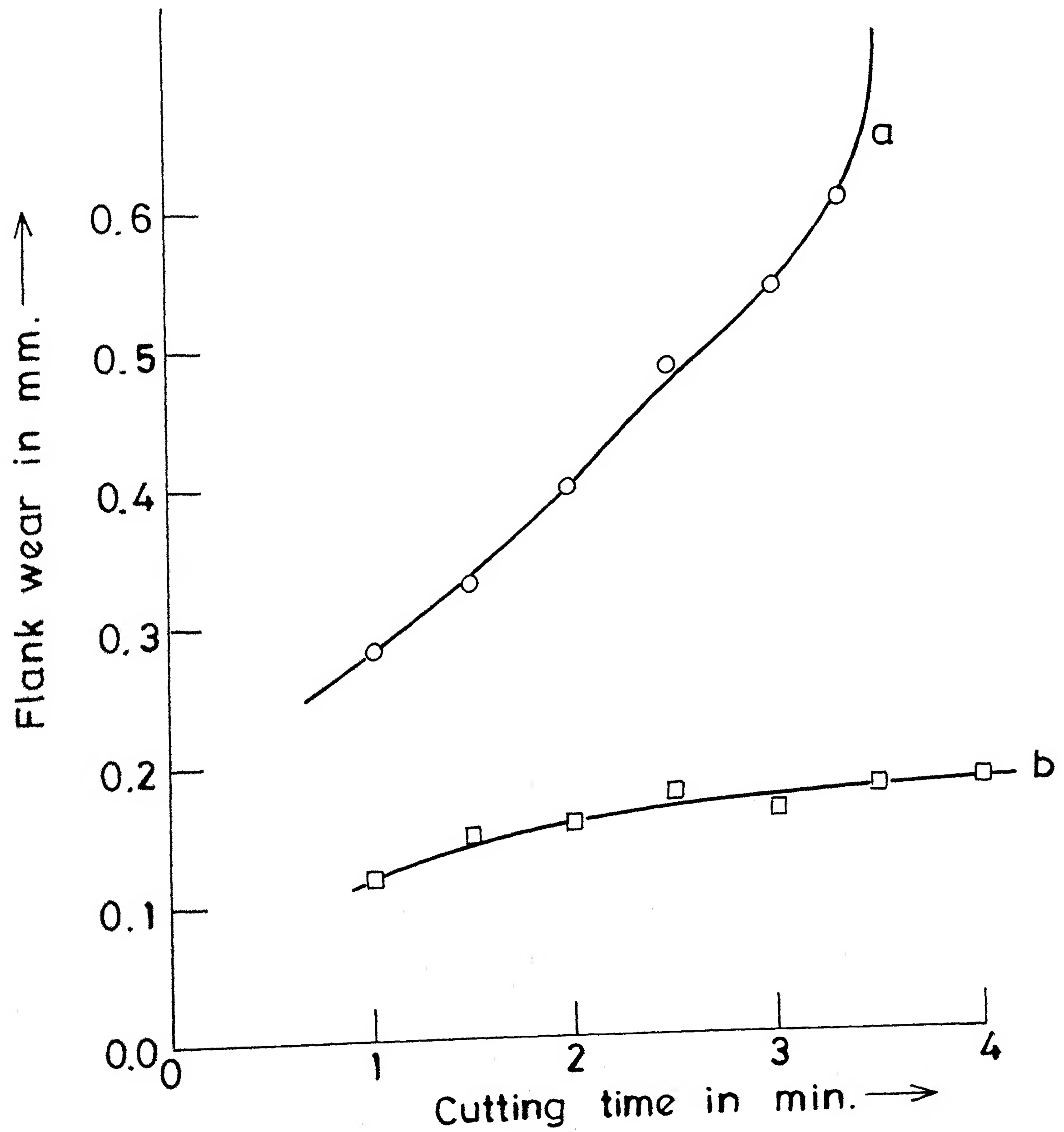


Fig. 3.12 Comparison of growth of flank wear.

Speed 100 m/min

Tool-HSS, W.P.-M.S.

Depth of cut-3 mm, feed-0.05 mm/rev

Side rake-15°, Side clearance-7°

follows:

$$T\theta^n = K$$

Reduction in tool face temperature is the one of the cause of improving the tool life.

The nitrogen must have some sort of positive boundary lubrication effect. It has been suggested (Wister (1936)) that nitrides could form on a sliding metal surface in the presence of nitrogen which would provide lower friction as a result of the increased hardness. Pahlitzsch [3] found an improvement in tool life over air by 240% using nitrogen. Further German work on this problem (Arwer, 1954) confirmed Pahlizsch's observation regarding nitrogen as a boundary lubricant.

3.4.2 Chip Deformation:

It was found that the radius of curvature of chip decreased appreciably when the water was applied as a cutting fluid. Curling of chips shifts the maximum temperature zone near the tool tip. Hence wear rate increases. On the other hand Radius of curvature of chip was increased when the liquid nitrogen was used. Less curling means displacing the maximum temperature point away from the wear zone. Hence reduction in chip curl reduces the wear rate of the tool.

At low temperature mild steel goes under ductile to brittle transition. It was previously thought that discontinuous

chips would be found at low temperature. But practically discontinuous chip was never be found. Rather than discontinuous chip very soft, straight and long chip was found. It means cutting was not performed below the transition temperature of mild steel. Interface temperature was practically measured of the the order of room temperature to 220°C. It means the liquid jet of nitrogen was not much efficient to carry out the heat. Some more appropriate technique must be thought to perform the cutting operation below transition temperature.

CHAPTER IV

MACHINING OF GLASS AND RUBBER

4.1 ABRASIVE JET MACHINING OF GLASS:

Introduction:

Abrasive jet machining (AJM) process finds its successful application for machining hard and brittle materials. The process canx also be used for machining of complicated shapes and contours. In the present work effect of low temperature on AJM of glass has been studied. AJM is most suitable for brittle material. Since these become more brittle at low temperature. Hence, better machining of glass is expected to be possible at low temperature.

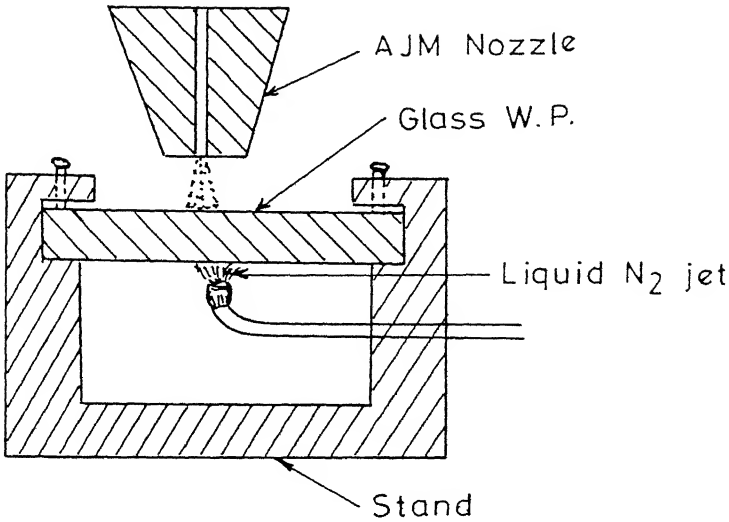
Brittle Erosion:

Under continual multiple impacts, of abrasive particle, micro-factures formed in brittle solids results in appreciable material loss by erosive wear. During solid particle impacts lateral cracks are produced in brittle materials below the impact site as a result of residual stress field. Erosion loss in brittle materials occurs due to intersection of lateral cracks from adjacent impacts. The formation of microcracks in brittle solids under such situations is a complex process and depends on the physical properties of the target and the projectile material and projectile velocity.

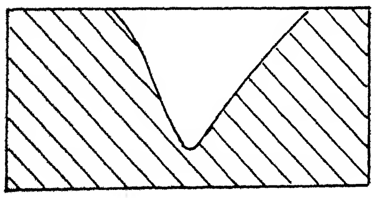
4.1.1 Experimental Procedure:

For the experiment, Abrasive Jet Machine fabricated at IIT Kanpur, was used. Simple window glass was taken as a work specimen. One piece of glass specimen was hold in the stand of the AJM machine. Stand-off distance of the nozzle was set-up and machining was done for a particular condition. After the machining operation one conical cavity was found on the glass piece. For obtaining the accurate result machining process was repeated three or four times under identical conditions. Now, the same workpiece was cooled with liquid nitrogen (as shown in Fig. 4.1) and machining operation was carried out, keeping all the conditions same. Experiments were repeated again three and four times at low temperature. For another set of experiments stand-off distance was changed and other machining parameters were kept the same. Machining operation was repeated at room temperature as well as at low temperature. In this way, keeping all the parameter same and varying only the stand-off distance, the machining process was repeated for the two temperature conditions.

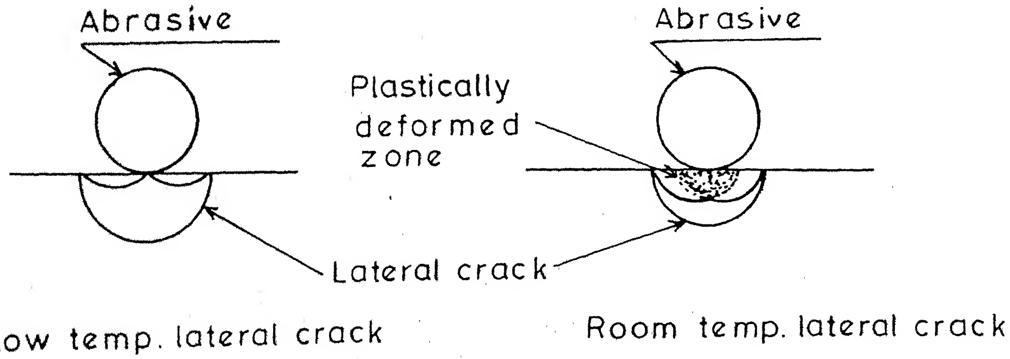
Dimensions (dia and depth) of each cavity machined were measured on a shadow graph. For each cavity produced, mean value of top dia and penetration were calculated. Machined cavity was assumed as a geometrical cone and its volume was calculated. All the results have been tabulated in the Table No. 4.1.



(a) Scheme of low temperature AJM process.



(b) A typical machined cavity profile.



(c) Probable schematic diagram of lateral crack.

Fig. 4.1 AJM of glass at low temperature.

4.1.2 Results and Discussion:

Results:

Figs. 4.2, 4.3 and 4.4 compare the top cavity dia, penetration and material removed, respectively, in both conditions for each stand-off distance. Figures show the top cavity dia. penetration and material removed increase at low temperature. Fig. 4.5 shows variation of material removed ratio with stand-off distance. It exhibits the effect of low temperature is much significant at small stand-off distance. Effect of low temperature become least at optimum M.R.R. condition.

Discussion:

Experimental results on AJM have established material removal rate increases at low temperature . Explanation can be given on the basis of properties of glass at liquid nitrogen temperature. Unfortunately, author could not find the detailed properties of glass at low temperatures. However, an attempt is made here to explain the present experimental results.

It has been established that fracture toughness of bcc, hcp and brittle materials decreases, as its yield strength increases, at low temperature [16]. Strength of glass increases at low temperature. Hence it is reasonable to assume, that the fracture toughness of glass will also decrease at low temperature. It has also been reported that the elastic modulus and shear modulus also increase at low temperature [10,25,26].

Table 4.1

Machining time - 30 sec.
Nozzle material - Tungsten carbide, dia 0.76 mm
Work piece material - Glass
Carrier Fluid - Dry air
Inlet pressure - 2.83 kg/cm^2, nozzle pressure - 2.4 kg/cm^2
Abrasive
Type - Aluminium oxide , Size - 30 μm
Mixture ratio - 0.268
Vibrator characteristics
Amplitude - 1.9 mm, Frequency - 8.33 c/sec.

SOD mm	Room Temperature Condition			Low Temperature Condition		
	Cavity top dia. (d), mm	Depth of penetration (h), mm	Volume removed $\pi/12\ d^2h$ mm^3	Cavity top dia. (d), mm	Depth of penetration (h), mm	Volume removed $\pi/12\ d^2h$ mm^3
2	1.835	1.326	1.689	2.341	1.78	2.554
4	2.053	1.777	1.961	2.503	2.09	3.428
8	3.101	2.107	5.304	3.562	2.373	7.882
10	3.727	2.178	7.92	3.76	2.384	8.824
12	3.88	2.33	9.183	4.072	2.267	9.819
16	3.633	1.487	5.138	3.842	1.885	7.284

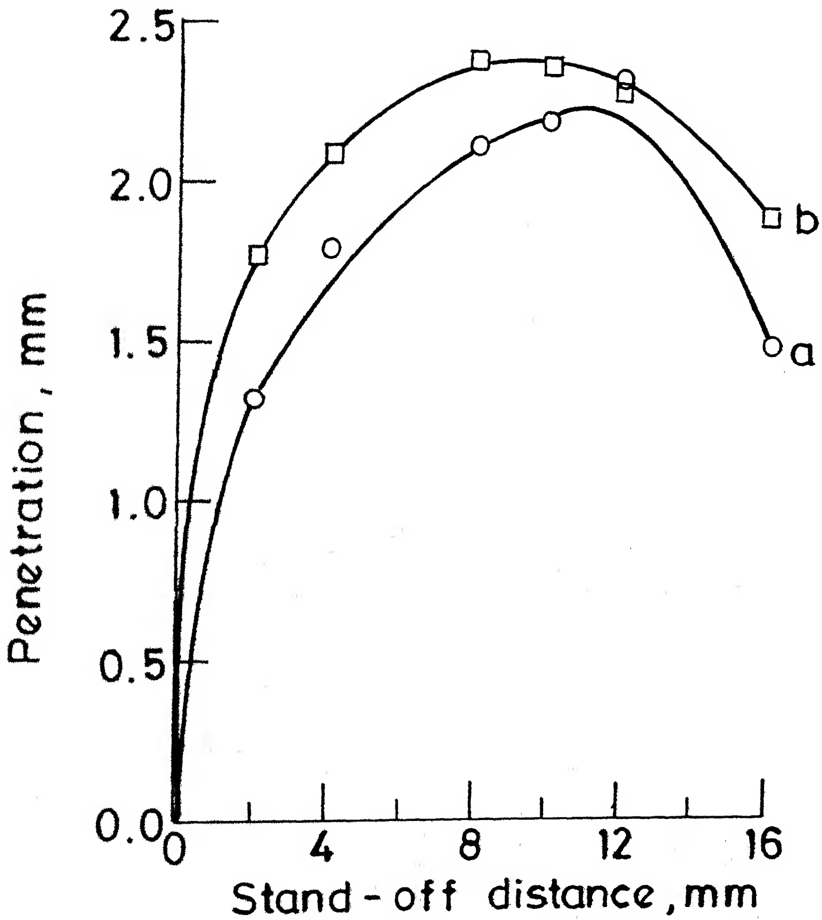


Fig. 4.2 Comparison of penetration.
(a) Machining at room temperature.
(b) Machining at low temperature.

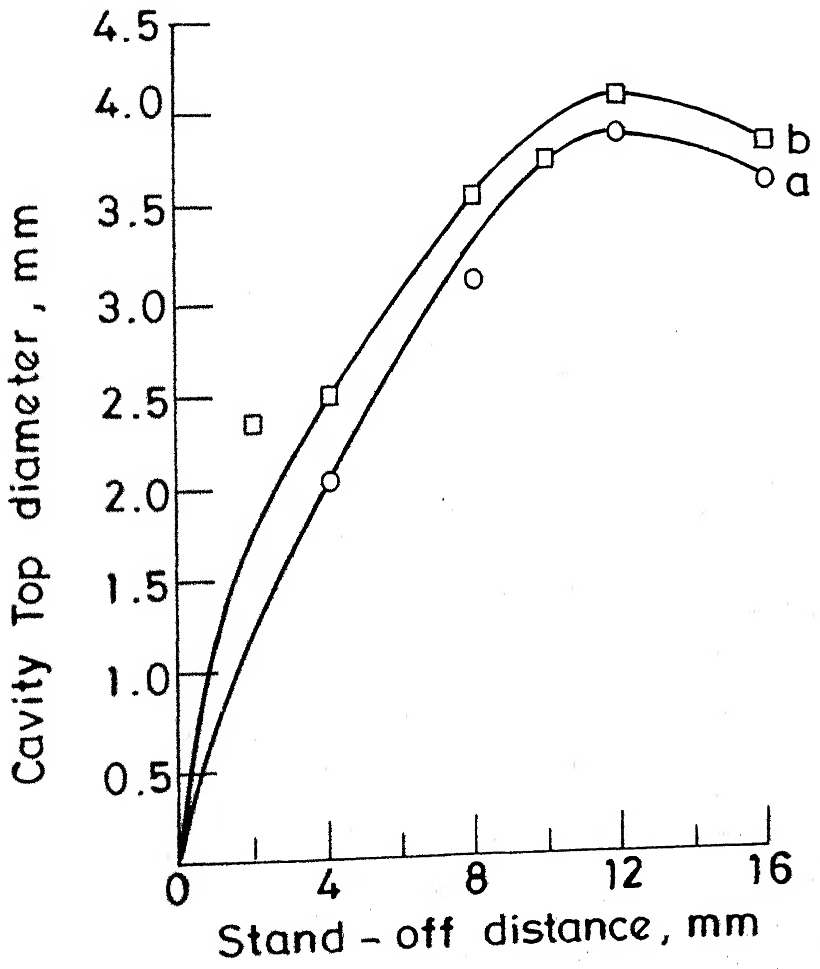


Fig.4.3 Comparison of cavity top diameter.
(a) Machining at room temp.
(b) Machining at low temp.

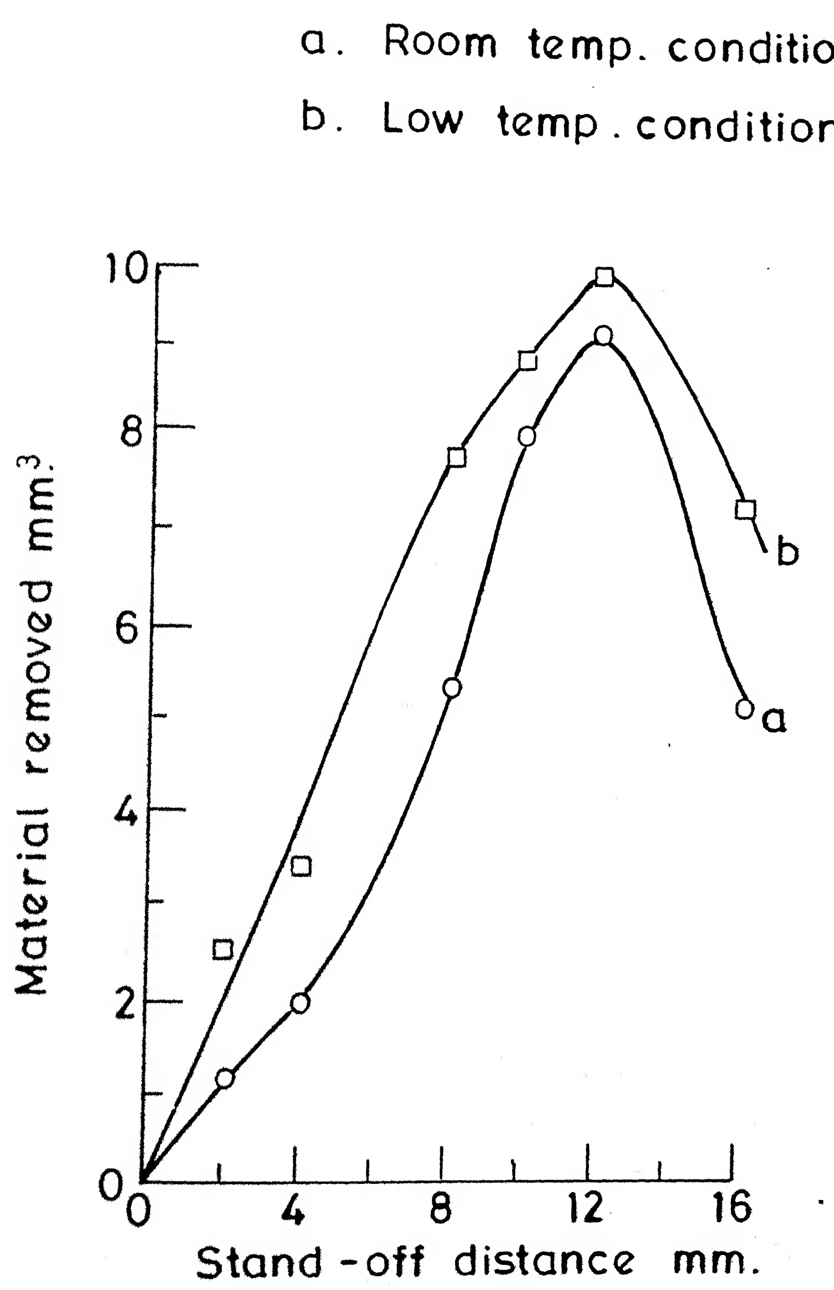


Fig. 4.4 Comparison of material removed in 30 sec.

Volume removal ratio, R.

$$= \frac{\text{Volume removed at low temp.}}{\text{Volume removed at room temp.}}$$

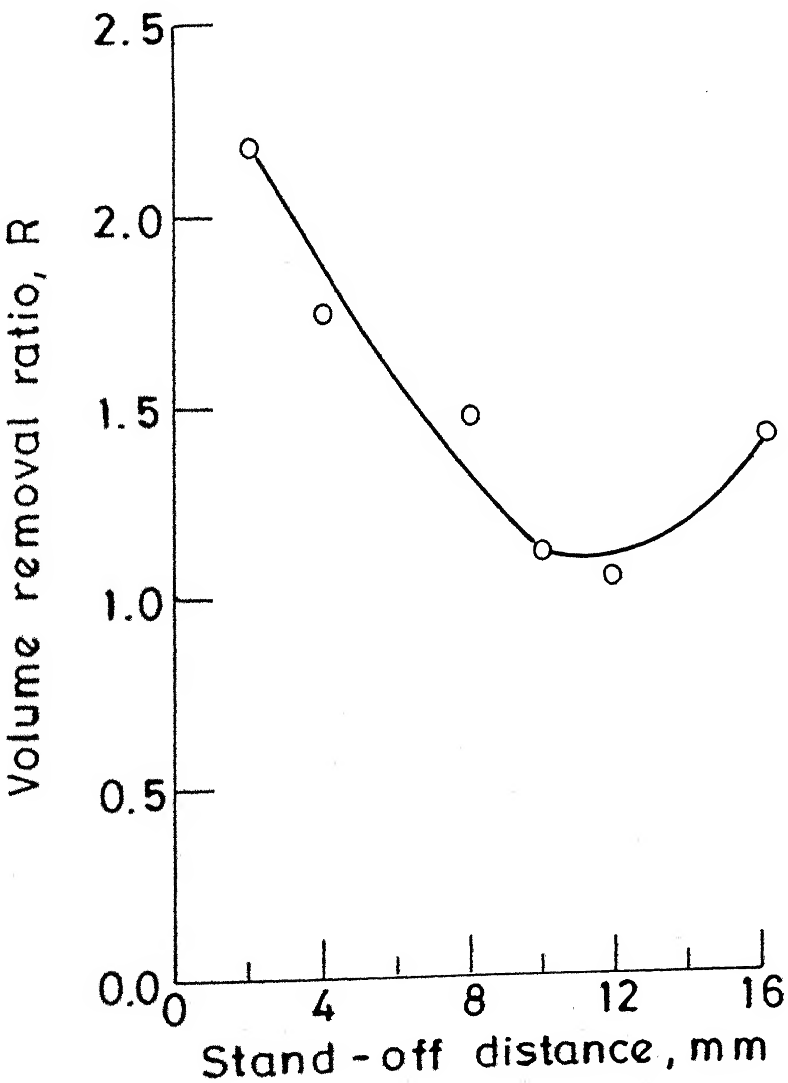


Fig.4.5 Variation of volume removal ratio.

Fatigue strength of glass decreases as the temperature decreased [16].

Following are the important mathematical models of material removal rate for machining of brittle materials.

1. $V_{max} = 0.7722 \frac{mU_x^{1.5}}{\rho^{\frac{1}{4}} \sigma^{\frac{3}{4}}}$ Neema and Pandey, Ist Model [27]

2. $V = 0.23125 (1-2\nu)\, m \frac{U_x^2}{\sigma}$ Neema and Pandey, 2nd Model [27].

3. $V = \frac{\lambda m d G^{3/2} \rho^{3/8} (U_x - U_t)^{11/4}}{K^{\frac{3}{2}} H^{\frac{11}{8}}}$ Verma and Lal [28]

4. $V = 5.9 f(\frac{d}{2})^{1/2} y_o^{1/2} (\frac{\sigma t}{H})$ Shaw model for untrasonic machining [29].

where,

V, V_{max}	=	Volume rate of material removal
U_x	=	Axial component of flow velocity
ρ	=	Material density of abrasive particle
σ	=	Strength of target material
σt	=	Stress developed in the tool
d	=	Particle diameter
G	=	Shear modulus of work material
H	=	Viker's hardness of target materials
K	=	Fracture toughness of work piece
U_t	=	Threshold velocity
λ	=	Function of stand-off distance

f = Frequency of active particle striking work surface

y_o = Amplitude of vibration

ν = Poisson's ratio

m = Mass flow rate of the abrasive particle

Above expressions reveal that strength or hardness of materials have controlling effect on material removal r ate. Material removal rate will decrease as the strength or hardness of materials increase. At low temperatures strength of materials increases significantly. Hence these models donot justify the present experimental results. Actually these models are based upon the elastic plastic deformation of materials.

Author thinks that at such a low temperature plastic deformation in glass is not possible. Folly and Levy [39] have reported that erosion resistance of steel increases with increase in ductility. They have further reported that erosion rate increases markedly below the ductile brittle transition temperature because of major decrease in ductility. As mentioned in Section 1.2, Pentland and Ektermanis have suggested the use of refrigerated abrasive slurry in Ultrasonic machining for enhancing material removal rate. Glass becomes more brittle at low temperature so there is no question of reduction in erosion rate.

The following equation expresses the collision of a sphere with a large flat plate. In such a situation, Hertz [30,31]

equation gives the average surface pressure q during elastic collision as:

$$q = \frac{2}{3}\left[\frac{40\rho}{\{\pi(\frac{1-\nu^2}{E}+\frac{1-\nu_p^2}{E_p})\}^4}\right]^{1/5} U_i^{2/5},$$

where,

ν, ν_p = Poisson's ratio of target and particle materials, respectively.

E, E_p = Modulus of elasticity of target and particle materials, respectively.

U_i = Particle impingement velocity.

ρ = Material density of abrasive particle.

Assuming,

q_l, q_r = Average surface pressure at low temperature and room temperature respectively

ν_l, ν_r = Poissons ratio of target material at low temperature and room temperature, respectively.

E_l and E_r = Modulus of elasticity of target material at low temperature and room temperature, respectively.

Taking ratio of surface pressure at low temperature to the surface pressure at room temperature expression reduces to

$$\frac{q_l}{q_r} = \left[\frac{\frac{1-\nu_r^2}{E_r}+\frac{1-\nu_p^2}{E_p}}{\frac{1-\nu_l}{E_l}+\frac{1-\nu_p}{E_p}}\right]^{4/5}.$$

Modulus of elasticity of glass increases by 15% and assuming 7% reduction in Poisson's ratio (which is reasonable) at low temperature.

$$\frac{q_l}{q_r} = 1.09$$

Hence for the same amount of loading the average surface pressure at low temperature will increase by 9% . Fracture toughness of glass decreases at low temperature as reported in Section 2.6.3. Evans and Wilshow [32] have shown that lateral crack length increases as the fracture toughness decreases.

To investigate the growth of lateral crack length at low temperature, one experiment was conducted. Abrasive jet machining was conducted for short time (10 and 20 seconds) to see the effect of a limited number of impacts on the surface of workpiece. In short time period of machining very limited abrasive particles will be effectively eroding the target. Experimentally it was found that area of damaged zone was increased at low temperature. This experiment indicates that lateral crack length has been increased under low temperature condition. Erosion takes place due to intersection of the lateral cracks developed in the work piece.* In this way above discussion can help to confirm the increment of material removal rate at low temperature.

* Also the impacting particle at periphery of the get are having less momentum energy. Hence they are less effective in eroding the material. Due to reduction in fracture toughness at low temperature more particles at periphery become effective.

4.2 MACHINING OF RUBBER AT LOW TEMPERATURE:

Machining of natural rubber at room temperature becomes very difficult. Rubber has low value of modulus of elasticity and high ductility. In many cases ice-water is used to harden it. It was thought that at low temperature rubber would become hard and machining would become easy.

One pilot experiment was conducted on lathe. For machining a 5 cm dia of rubber cork was taken. It was mounted on lathe with the help of special fastening arrangement. Liquid nitrogen was spread on the rubber cork to cool it. When it was cooled sufficiently, cutting operation was started. Forces were also tried to be measured. But rubber cork become too hard to be machined at liquid nitrogen temperature. HSS tool was worn out just after the start of cutting. Cutting forces was increased too much.

Conditions of rubber, indicated that it had been cooled much below than the glass transition temperature. At low temperatures after an specific point rubber looses its rubber properties. It becomes just like glass. This temperature is called glass transition temperature. Experiment indicated that rubber reached such a state in which conventional machining was not possible. This glass transition state was tested by AJM. One rubber strip was taken and cooled by liquid nitrogen. After cooling it AJM was conducted on the cooled strip. Very fine hole was produced on the rubber strip. It means fine hole can be made on rubber after cooling it upto glass transition temperature. No measurement however, were taken in this case.

CHAPTER V

CONCLUSIONS AND SCOPE OF FURTHER RESEARCH

5.1 CONCLUSIONS:

On the basis of various experimental observations and results obtained by the author the following conclusions about low temperature machining can be drawn:

(i) Cutting force is reduced.

(ii) Shear plane angle increases.

(iii) Tool life increases.

(iv) Mean chip tool interface temperature decreases.

(v) Curling of chip decreases.

(vi) Soft, straight, continuous and bright chip are produced.

(vii) In case of AJM, top cavity dia, rate of penetration and material removal rate increases.

5.2 SCOPE OF FURTHER RESEARCH:

In case of high strength metals and alloys heat generated in cutting process is much more. If the material have low thermal conductivity, general coolants fail to remove the heat generated in the cutting operation. In much of the cases machining operations are done at low cutting speeds. Using liquid nitrogen as a cooling agent, one can go for higher cutting speeds.

Present work on AJM is the only initiation in this field. Many interesting results at low temperatures can be found in this field. It opens the wide area of research to increase the efficiency of AJM upto the economical level.

5.2.1 Application on Titanium and its Alloys:

Titanium alloys are among the most trouble some materials to machine at practical cutting speeds. The greatest difficulty in machining these alloys stems from the very high cutting temperatures, experienced under conditions that are usually used for most other materials. The extent to which cutting temperatures for titanium alloys are found to exceed those for other metals is shown in Fig. 5.1.

Stainless steel has greater specific cutting energy than those of AISI1113 steel. But for titanium specific energy consumption is less than that of AISI1113 stee.

The very high tool temperatures experienced when machining titanium have been shown to be due to the very low value of $(K \rho C)$ for titanium. It can be understood with the help of equation,

$$\bar{\theta}_t \approx u \left(\frac{Vt}{K\rho C} \right)^{1/2}$$

where,

$\bar{\theta}_t$ - tool-chip interface temperature

u - total cutting energy per unit volume

V - cutting speed

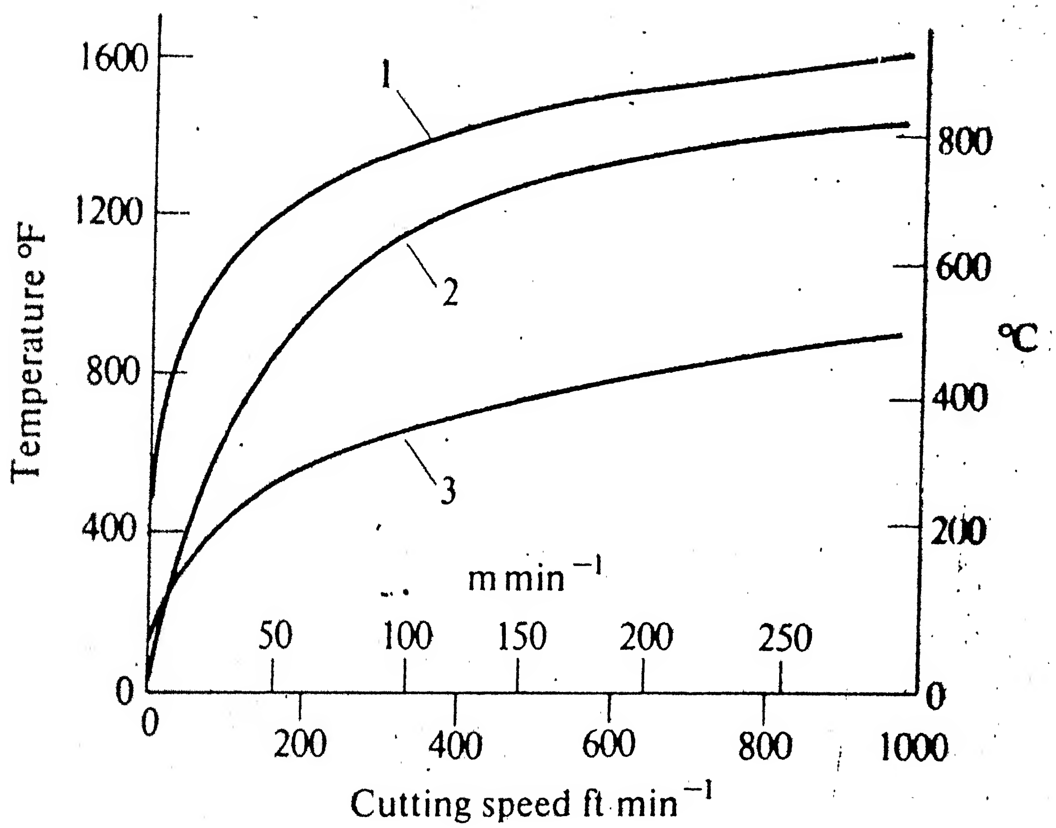


FIG. 5.1: VARIATION OF MEAN CHIP-TOOL INTERFACE TEMPERATURE WITH CUTTING SPEED FOR (1) TITANIUM ALLOY, (2) 18-8 STAINLESS STEEL, (3) AISI 1113 STEEL TURNING WITH K2S CARBIDE TOOL[3].

t - undeformed chip thickness

K - coefficient of thermal conductivity

ρC - volume specific heat of work.

High tool temperature terminates the tool life by flank wear and/or deformation of the tool. Very short tool life becomes the main problem of machining titanium. Apart from deformation, diffusion wear seems to be the main process, responsible for the wear both of HSS and carbide tool when cutting titanium alloys.

Use of liquid nitrogen will reduce the tool chip interface temperature to the lower level and solve the tool life problem to a satisfactory state. Machining can be done at higher speed to obtain greater metal removal rate.

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